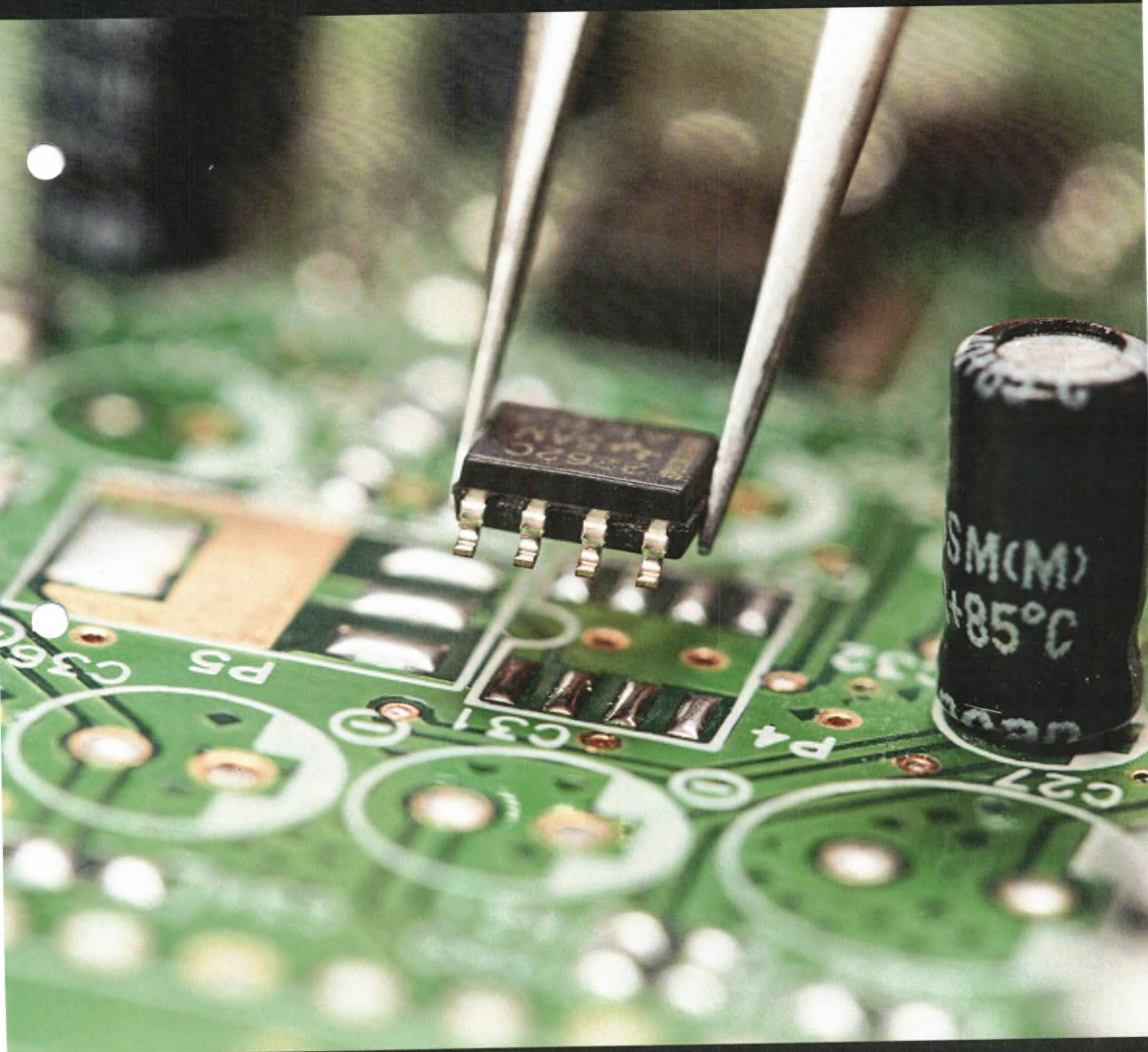
TAFE NSW

Amplifier fundamentals



tafensw.edu.au

Student Workbook

Author: Barry Duncan

Amplifier Fundamentals

Version 2.0 - July 2022

The Electronics Section
Ultimo Campus of TAFE NSW
Mary Anne St
Ultimo NSW 2007

Contents

Introduction

This workbook has been written to help students satisfy the assessment requirements for the following Units:

- UEEEC0067 - Troubleshoot basic amplifier circuits

More information about electrotechnology training packages and the above Units can be found at www.training.gov.au/home/tga. Type the course/unit number in the "Quick search" and press return.

Textbooks

The following textbooks can be used to supplement the notes in this workbook. Most (if not all) of these books are available from the library in Building D.

- Bell (1986). *Electronics devices and circuits* (3rd edition). Reston Publishing.
- Boylestad & Nashelsky (2002). *Electronic Devices and Circuit Theory* (8th edition). Prentice Hall.
- Donovan (2002). *Electronics Mathematics* (2nd edition). Prentice Hall.
- Edwards & Myer (1993). *Electronics; a basic course* (2nd edition). McGraw Hill.
- Fiore (2001). *Op amps and linear integrated circuits*. Thompson Learning.
- Floyd (2002). *Electronic Devices* (6th edition). Prentice Hall.
- Gates (2001). *Introduction to electronics* (4th edition). Thompson Learning.
- Granger (2000). *Amplifiers*. Educational Texts.
- Hazen (1991). *Exploring Electronic Devices*. Saunders Publishing.
- Ludeman (1990). *Electronic Devices and Circuits*. Saunders Publishing.
- Malvino (1998). *Electronic Principles* (6th edition). McGraw Hill.
- Paynter & Boydell (2002). *Electronics Technology Fundamentals*. Prentice Hall.

Lesson organiser

The following is a suggestion only. It may be changed to meet student needs and/or different modes of delivery.

Lesson	Section	Topics and activities
Before starting (ideally)	Required reading	■ Work health and safety ■ Using sustainable energy practices ■ Communication and documentation ■ Test and measurement devices and their safe use
1	1	■ Amplifier basics including: what amplifiers do; amplifier classifications; calculating gain (as a ratio); input-output phase relationships; distortion; overdriving amplifiers; clipping; cascaded amplifiers; and the process for measuring gain ■ Practise measuring the voltage gain of single stage and multistage (cascaded) amplifier circuits using an oscilloscope
2	2	■ Calculating gain of single stage and multistage amplifiers in decibels ■ The purpose of expressing gain in decibels ■ Practise measuring the voltage gain of commercially available domestic hi-fi amplifiers
3	3	■ Amplifier frequency response ■ Practise measuring the frequency response of amplifier circuits using an oscilloscope
4	4	■ Loading of amplifier outputs ■ Loading of sources by amplifiers ■ Practise measuring the unloaded and loaded voltage gain of amplifier circuits using an oscilloscope
5	5	■ **Revision** ■ Op amps operated in open-loop mode ■ Comparators ■ Practise measuring the output of comparators using a DMM
6	6	■ The non-inverting and voltage follower op amp configurations ■ Closed-loop op amp bandwidth ■ Troubleshooting non-inverting op amp configurations ■ Practise measuring the voltage gain and bandwidth of amplifier circuits using an oscilloscope
7	7	■ The inverting and summing amplifier configurations ■ Troubleshooting inverting op amp configurations ■ Practise measuring the voltage gain and bandwidth of amplifier circuits using an oscilloscope
8	8	■ **Revision** ■ The differencing amplifier ■ Practise measuring the voltage gain of amplifier circuits using an oscilloscope
9	■ **Possible assessments - Refer to UAG for details**	

Student notes

Required reading

Purpose

These notes are provided to support your revision on aspects of this Unit that have been taught before in other Units (typically more than once) and will not be taught again but may be assessed.

This issue is explained in more detail on the following pages.

Introduction

As you probably know, *units of competence* that make up qualifications in the Electrotechnology Training Package (like CIII Electronics and Communications) prescribe what must be taught and assessed.

This is done using *elements of competence* together with *performance criteria* for each element. More detail on these is provided in the *assessment requirements* for the unit using two lists: one is the list of *performance evidence*; and the other is the list of *knowledge evidence.*

There are some performance criteria (together with performance evidence and/or knowledge evidence in the assessment requirements) that appear in many units and these include items on the following topics:

- work health and safety (WHS)
- using sustainable energy practices
- the appropriate use and completion of documentation
- appropriate communication with supervisors, customers and other stakeholders.

It makes sense that these performance criteria are common to multiple units because, taking WHS as an example, it's not reasonable to claim competence when the work was completed successfully but in an unsafe way.

As well as the topics listed above, there are performance criteria and/or assessment requirements related to electrical/electronic theory and practice that appear in two or more units. This occurs when the people who have developed the training package (not TAFE NSW) have decided that it's appropriate that they should do so. An example of this for UEEEC0067 is the requirement for you to demonstrate your knowledge of how to connect a digital multimeter to a circuit to measure potential difference which you have previously learnt about when undertaking CD0043 (formerly UEENEEE104A).

Importantly, where all these topics have been comprehensively taught before, it is usually unnecessary to teach them a second or third time. That said, we are still expected to ask you to provide knowledge evidence and/or performance evidence possibly by answering questions on these topics in the theory test and/or demonstrating your skills on these topics during the practical tests.

For this reason, the following information and/or notes are provided for you to read and use to ensure that you can satisfy the assessment requirements for this unit.

Work health and safety (WHS)

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0067), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to WHS and their associated knowledge evidence and performance evidence:

1.1 - Work health and safety (WHS) requirements and workplace procedures for relevant work area are identified, obtained and applied (UEECD0007 references: 1.2, 1.3 & 1.4)

1.2 - WHS risk control measures are applied in accordance with workplace procedures prior to commencing work (UEECD0007 references: 1.2, 1.3 & 1.4)

2.1 - WHS risk control measures and workplace procedures are applied (UEECD0007 references: 1.4, 1.6, 2.1 and 2.4)

2.2 - Need to test and measure live work is determined in accordance with WHS requirements and workplace procedures (UEECD0007 references: 1.2, 1.3 & 1.4)

3.1 - WHS risk control measures and procedures are applied (UEECD0007 references: 3.1 to 3.4)

3.2 - Worksite is cleaned and made safe in accordance with workplace procedures (UEECD0007 references: 2.6)

Source: https://training.gov.au/Training/Details/UEEEC0067

As you may already be aware:

- WHS is taught and assessed in a dedicated unit, CD0007 (formerly E101A) and you should have a pass for this unit
- The performance criteria listed above are underpinned by, and/or are identical in substance to, the performance criteria from CD0007 (and E101A) indicated in the brackets above

Importantly, the knowledge and skills needed to perform these performance criteria are identical to those needed to repair basic amplifier circuits. This means that you already have the ability to demonstrate your knowledge of, and demonstrate your ability to carry out, these performance criteria in the context of this unit.

However, if your unsure and would like to read more information about these performance criteria, please refer to your learner resources for CD0007/E101A that specifically address them.

Note: If you have not successfully completed CD0007 or E101A, please bring this to the urgent attention of the teacher before undertaking any of the simulated workplace tasks.

Using sustainable energy practices

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0067), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criterion:

2.6 - Fault-finding activities are conducted efficiently minimising unnecessary waste of materials, damage to apparatus, the surrounding environment or services applying sustainable energy practices.

This includes knowing about sustainable energy principles and using sustainable energy practices.

Sustainability is a much used word now that describes growing global response to the short and long term negative effects on the planet of certain human activities, particularly in relation to climate change and pollution. It's accepted that, without drastic action, both problems will likely make living on this planet more difficult (due to extreme weather and toxic environments) that, in turn, risk causing drought, famine, war and the failure of democratic governments and even whole nation states.

R J Fuller (Deakin University, 2005) describes four principles that underpin sustainability:

- Futurity - The concern for future generations
- Environment - The concern to protect the integrity of eco-systems
- Equity - The concern for the poor and disadvantaged
- Participation - The notion that individuals can participate in decisions affecting them

An essential element of the global response to climate change is the switch to sustainable energy. Energy is said to be sustainable if it "meets the needs of the present without compromising the ability of future generations to meet their own needs." Underpinning this are the sustainable energy principles which include (but are not limited to):

- Reducing our use of non-renewable energy sources (like the fossils fuels which includes coal, gas and oil)
- Increasing our use of renewable sustainable energy sources (like solar just to name one of many).

Fuller's fourth principle is important because it means that individuals, including you, can contribute directly and indirectly to sustainable energy principles by using sustainable energy practices where possible. Direct action that can be taken includes (but is not limited to):

- Switching off equipment not in use
- Turning off lights when leaving a room with nobody in it
- Opening windows to cool rooms instead of turning on room air-conditioning
- Using natural lighting
- Minimising waste
- Recycling waste
- Using public transport to and from work
- Drinking tap water

Indirect action that can be taken, includes (but is not limited to) encouraging your employer to:

- Using more energy efficient lighting
- Using more energy efficient equipment
- Reducing (in winter) and increasing (in summer) the temperature setting of air conditioning so that to uses less energy
- Switching to using sustainably sourced and/or sustainably manufactured materials
- Switching to an SEU energy provider

With all that said, every workplace is different so what works with one may not work with another.

Communication and documentation

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0067), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to workplace communication and documentation and their associated knowledge evidence and performance evidence:

1.3 - Scope of fault is obtained from documentation or discussions with relevant person/s to determine scope of work

1.4 - Instructions for coordinating work with others are obtained from relevant person/s and applied

1.5 - Materials required for the work are determined in accordance with workplace procedures

1.6 - Tools, equipment and testing devices required for work are obtained and are checked for correct operation and safety

3.3 - Justification for troubleshooting solutions is provided in the required format

3.4 - Work completion is reported and relevant person/s notified in accordance with workplace procedures

The specific knowledge required to satisfy these performance criteria is specific to each workplace setting. However, the skills are generic and so are transferable between workplace settings including simulated workplace settings at TAFE NSW. This means that, when you undertake the in-class simulated workplace tasks and the practical test, you are expected to demonstrate your skills in this regard.

Importantly, while undertaking the in-class simulated workplace tasks and/or the practical tests for this unit at TAFE NSW, the following applies to key terms in the performance criteria above:

- "Relevant person/s" refers to the class teacher
- "Others" refers to the class teacher and other students in the class
- "Materials" refers to components and training aids needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list
- "Workplace procedures" refer to the written and verbal procedures and instructions provided by the teacher for the safe and proper conduct of skill practise exercises
- "Tools, equipment and testing devices" refers to tools and test equipment needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list and/or mounted on the workbenches

- "Reported... in accordance with workplace procedures" refers to the requirement for students to record their measurements, other results, and answers to questions on the skill practice exercises and/or any handouts that must be submitted to the teacher.

The following is the procedural requirement for undertaking the simulated workplace tasks that form the basis of skill practise exercises.

- Students must have permission from the teacher to start every skill practice exercise.
- Students must work individually on every skill practise exercise, or in pairs with the permission of the teacher (but never more than two per group).
- Students must perform a WHS risk assessment at the start of every skill practice exercise to ensure the safety of themselves and others.
- Students are to bring to the attention of the teacher any hazards that they identify for which there are they cannot implement appropriate control measures.
- Students are to collect equipment from the trolley in a safe and orderly manner having respect for the reasonable needs of other students.
- Students are to follow the written instructions in every skill practice exercises in correct order and in total including any qualifying notes.
- Students are expected to record their measurements, other results and answers to questions for every skill practice exercise and/or any handouts that must be submitted to the teacher.
- Students are expected to call the teacher to check their work when instructions direct them to do so.
- Students are expected to retake any measurements and reattempt and/or correct any of their answers to questions when reasonably directed to do so by the teacher.
- Students are not to return their equipment to the trolley or leave **until** they have completed the skill practice exercise and their work has been checked by the teacher.
- Students are expected to submit their work to the teacher by the due date when required to do so.
- At the completion of every skill practice exercise, students are expected to return all equipment to the trolley tidily (unless directed otherwise by the teacher) and ensure that the workspace is left cleaned and safe.
- Students are to bring to the attention of the teacher any faulty test equipment, tools and components.

Test and measurement devices and their safe use

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0067), you're expected to demonstrate your knowledge of:

- Electronic testing and measuring devices and techniques including:
  - test/measuring devices and their application including:
    - multimeters
    - function generators
    - oscilloscopes
  - connection of test/measruing devices into a circuit including:
    - ensuring circuits are isolated
    - testing or measuring on live and operating system safely

You first learnt about multimeters and practised using them on live circuits when undertaking unit CD0043. And you have learnt about, or are currently learning about, the correct use of function generators and oscilloscopes in EC0074.

Importantly, you're expected to know the general principles of using multimeters, function generators and oscilloscopes the safety precautions around working on live circuits. However, if your unsure that you are able to demonstrate your knowledge of these tasks or your ability to carry them out, the following notes have been provided here for your convenience for you to read.

Safety considerations when connecting test and measurement devices to circuits
When using a multimeter or oscilloscope to test and measure electronics equipment, there are two important safety measures that can minimise the risk of your being fatally electrocuted.

The first relates to the fact that technicians usually must necessarily test mains-operated electronics equipment (like a hi-fi or PVR) that is plugged-in, turned on and operating. To minimise the risk of electrocution, you must ensure that the equipment that you're testing or repairing is plugged into a power point that is protected at the switchboard by a residual current device (RCD). You can check whether the building's powerpoints are RCD protected by looking inside the switchboard. Figure 1 below shows an example of what to look for.

Figure 1

Up close, RCDs look like the example in Figure 2 below and there should be at least one row of these devices in the switchboard mounted side-by-side. RCDs are easily recognised by the fact that they're switched devices and often they have an in-built test feature too.

Figure 2

RCDs have been designed expressly for the purpose of preventing people and animals from a sustained direct connection to mains which can be fatal.

If the switchboard is older it may use semi-enclosed cartridge fuses instead of RCDs and an example is shown in Figure 3 below. Importantly, being fuses, these devices are designed to protect equipment and prevent fires but they **do not** prevent people/animals from potentially fatal electrocution. You should avoid powering the equipment that you're testing/reparing from power points that are only protected at the switchboard by these fuses.

Figure 3

If you can't access the switchboard to see what's inside, or you know for certain that the power point is not RCD protected, then plug the equipment that you're testing into the powerpoint of a powerboard that is RCD protected instead. An example is shown in Figure 4 below - Notice the RCD at the left end (which includes a button for the test feature).

Figure 4

Take care when purchasing protected powerboards because there are many that offer "surge" and/or "overload" protection. While these features are useful, they don't provide protection from electrocution. Powerboards that are RCD protected will state this clearly and are usually a fair bit more expensive than simple surge and overload protected powerboards.

The second safety measure you must employ when connecting multimeters to live equipment, involves never doing so with your fingers touching any of the probe's metal parts. Figure 5 below shows the correct way to hold the probes. Notice that the person holds the probes behind the their slip barriers.

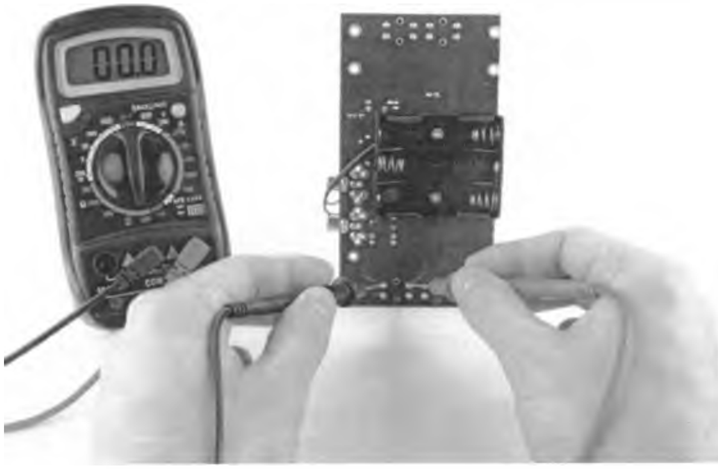


Figure 5

Similarly, when connecting oscilloscope probes to live equipment, ensure that your fingers don't make any contact with the circuit board or the probe's metal parts at the tip. Figure 6 below shows the correct way to hold oscilloscope probes. Notice that the person holds the probe behind the slip barrier if, they've rested their hand on the workbench not the circuit board.

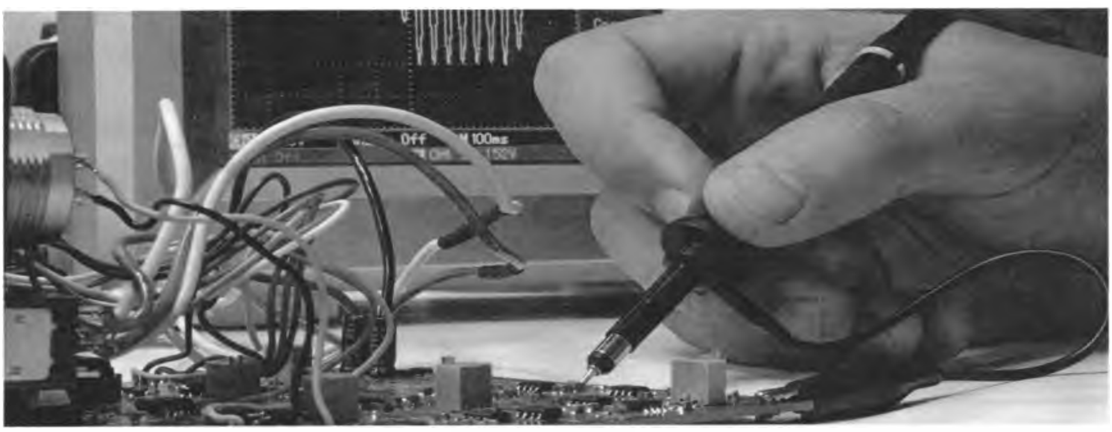


Figure 6

Student notes

Section 1 An introduction to amplifiers

Purpose To develop your ability to calculate and measure the gain performance of small signal amplifiers.

Objectives Once you have completed this section you should be able to:

- Explain the purpose of small signal amplifiers and where they are used
- Calculate the voltage/current/power gain of an amplifier (as a ratio)
- Calculate either the input or output voltage/current/power of an amplifier given its gain (as a ratio) and the output or input voltage/current/power
- Calculate the total gain of a cascaded amplifier (as a ratio)
- Explain the term *input/output phase relationship*
- Explain the term *distortion*
- Explain what *overdriving* an amplifier means and the effect on the amplifier's output signal
- Use an oscilloscope to measure the voltage gain of single stage and multistage (cascaded) amplifiers

What is an amplifier?

An amplifier is an electronic circuit that takes an input signal and produces a copy of the signal on its output that is usually larger (though, not always). A hi-fi amplifier is a typical example - it takes a small electrical signal from a sound source, such as a CD player, and amplifies the signal to a level where it can drive a set of loudspeakers.

Schematic symbol

The general symbol for an amplifier is shown in Figure 1.

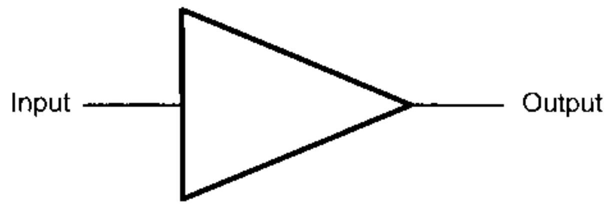


Figure 1 *The general symbol for an amplifier*

You have seen amplifiers before

Do you remember teachers at school using mega-phones or loud-hailers in the school yard? Perhaps you've seen them being used by speakers leading protest marches. The loud-hailer is a very simple example of an amplifier.

The part of a loud-hailer that you speak into (the input) has a microphone that converts sound to an electrical signal. Circuits inside the loud-hailer make this electrical signal bigger. Then the signal is converted back to sound by a loud speaker (the output). The sound that comes out of a loud-hailer is many times louder than the sound that went into it because of the amplifying nature of the circuits inside; they are amplifiers.

Other examples of common systems that use amplifiers include stereo systems and portable stereos. These take a small signal from the CD player or tape-deck and change it to a signal powerful enough to produce music out of the speakers or headphones.

Amplifiers are used inside radios, televisions & monitors, mobile phones (for the headphone and speaker outputs), public address systems, and communications transmitters. Amplifiers are the building block of all electronics (even digital electronics) and, as a technician, you're expected to know a lot about them.

Where does the output power come from?

Amplifiers **DON'T** create energy! So how can an amplifier take a small signal and produce a larger one? Where does the extra energy come from? The answer is from a DC power source or "power supply".

Figure 2 below shows a DC power supply connected to a "single rail" amplifier's power connections (called *Vcc* and *Vee* for reasons not explained here). The power supply's positive terminal is connected to the amplifier's *Vcc* input and it's negative terminal is connected to the amplifier's *Vee*. Notice that the power supply's negative terminal is also connected to the output device (as speaker in this example) so this power supply connection is usually called "common" because it's connected to all three devices.

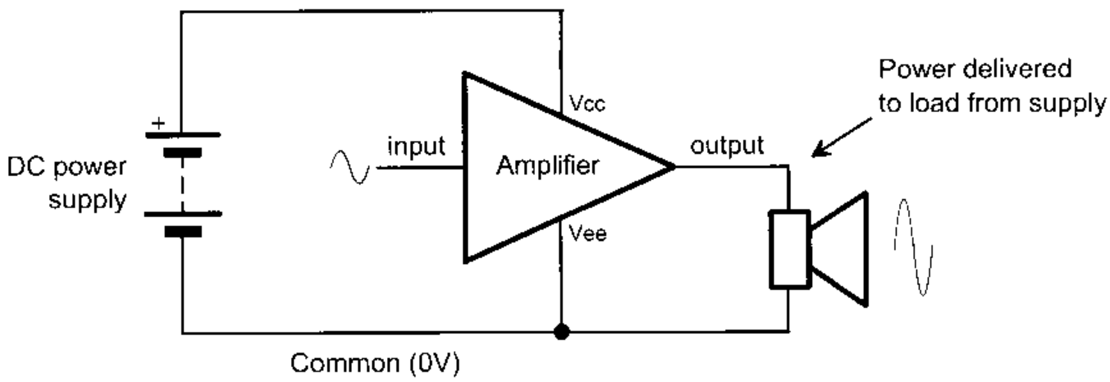


Figure 2 *The power delivered to the speaker (in this example) comes from the DC power supply*

In a system that has a connection to "earth" via a three-pin mains plug, the earth is connected to common and this is shown in Figure 3 below.

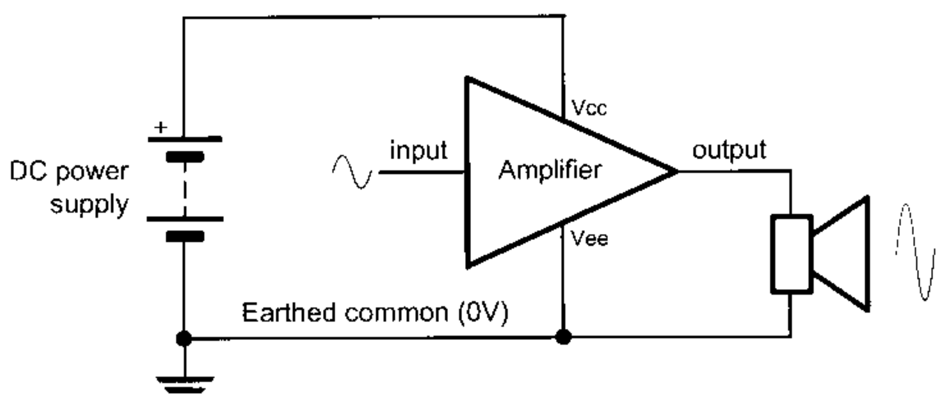


Figure 3 *The common is connected to earth via a three-pin mains plug*

For convenience, the circuit in Figure 3 can be drawn as shown in Figure 4 below. In fact, this is so convenient that the earth symbol is widely use to represent common even when common isn't connected to earth and this is done throughout this workbook.

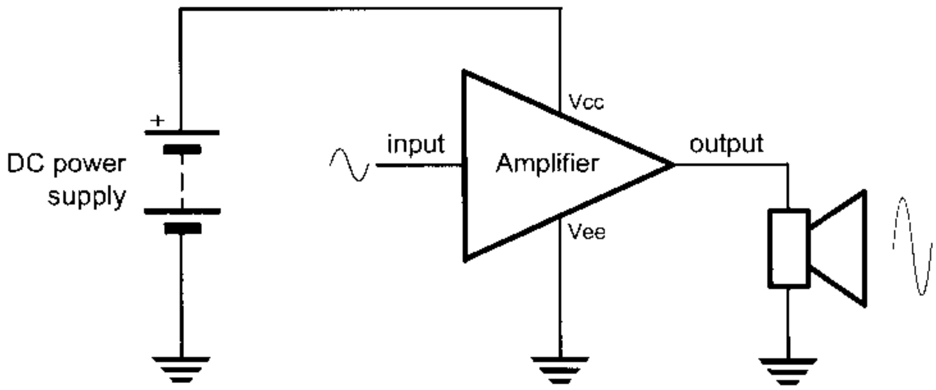


Figure 4 *Figure 3 redrawn*

Figure 5 below shows two DC power supplies are needed to supply a "dual rail" amplifier (whose power connections are called *+Vcc* and *-Vcc*). The positive terminal of the power supply labelled *PS1* is connected to the amplifier's *+Vcc* input and the negative terminal of the power supply labelled *PS2* is connected to the amplifier's *-Vcc*. The negative terminal of *PS1* is connected to the positive terminal of *PS2* and this junction is the circuit's common.

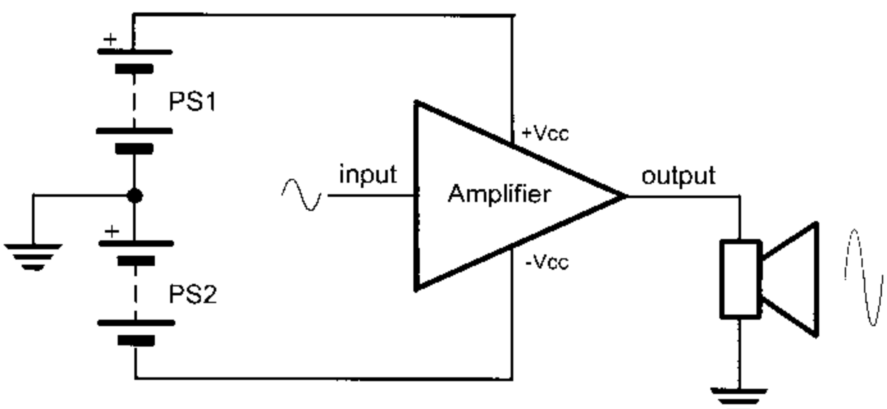


Figure 5 *The power supply connections for a "dual rail" amplifier*

Amplifier classifications

There are many ways of classifying amplifiers and a common method is by what they amplify; that is, voltage, current or power. So, you can have voltage amplifiers, current amplifiers and power amplifiers.

Another is to talk about what they are used for. For example, there are radio frequency (RF) amplifiers used in communications equipment such as broadcast radio and television. There are also non-linear amplifiers such as a tone-control amplifier in a hi-fi system, pre-amplifiers for a pick-up on turn-tables in hi-fi systems, and amplifiers that convert current input to voltage output or vice versa for impedance matching.

Regardless of the classification, all the amplifiers that you will learn about in this subject have one thing in common: they are all small signal amplifiers. Small signal amplifiers usually have a voltage input measured in millivolts and a larger output voltage which is likely to still be measured in hundreds of millivolts or volts. You will find them in many places such as test equipment (eg a CRO) and the front end of audio amplifiers in hi-fi systems and televisions.

We will not be looking at specific discrete component amplifier circuits in this unit - You'll do that in a later unit. Here we will be considering small signal amplifiers from a "black-box" perspective only. That is, we don't care what is inside the box or how the amplifier is made. We are only interested in some of its characteristics, how the amplifier performs and what happens when you connect amplifiers together one after another.

Amplifier input-output connections

The input to an amplifier is a signal of some sort that can come from a microphone, an antenna, a musical instrument or a hi-fi component (such as a CD player). It is common in the electronics industry to call the input device a *signal source* regardless of what it is. A signal source can be represented as shown in Figure 6 below.

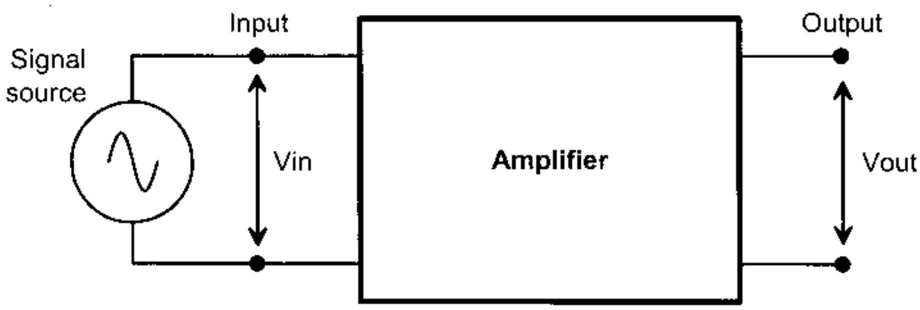


Figure 6 *An amplifier with an input signal connected to it*

The output of an amplifier can be connected to a loud speaker, an antenna or the input of another circuit (such as another amplifier). It is common in the electronics industry to call the device connected to the amplifier's output the *load* and the amplifier is said to *drive* the load. As all loads are resistive to some extent, the generic symbol for the load is a resistor and this shown in Figure 7.

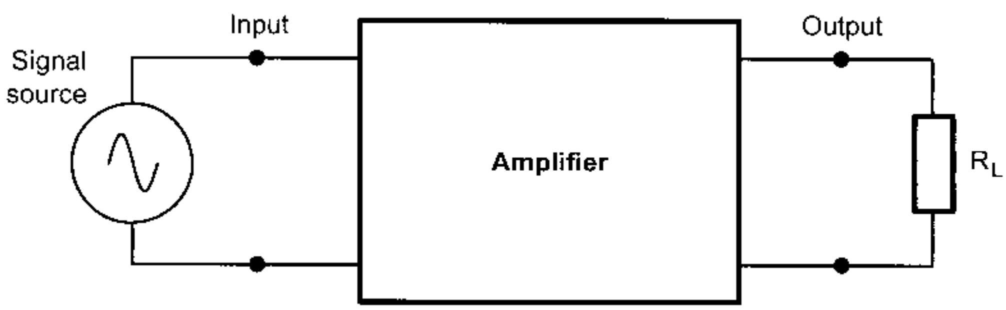


Figure 7 *Input and output connections to an amplifier*

Gain

The terms *gain* and *amplification* are used to describe how many times bigger the output of an amplifier is compared to its input. The voltage gain of any amplifier can be calculated using the equation:

$$\boxed{Av = \frac{Vout}{Vin}}$$

Where:
Av is the voltage gain (as a ratio)
Vin is the input voltage (in volts)
Vout is the output voltage (in volts)

Let's try an example. An amplifier fed with a 50mV input signal produces a 2V output. What is the amplifier's gain?

$$Av = \frac{Vout}{Vin}$$

$$Av = \frac{2V}{50mV}$$

$$Av = 40$$

Like all equations, the gain equation can be transposed to find one of the other variables when the gain is known. For example, what is the output signal of an amplifier with a gain of 25 and a 10mV input signal?

Solution: Starting with $Av = \frac{Vout}{Vin}$ and multiplying both sides by *Vin* gives:

$$Vout = Av \times Vin$$

$$Vout = 25 \times 10mV$$

$$Vout = 250mV$$

Or, what is the input to an amplifier with a gain of 125 and an output of 300mV?

Solution: Starting with $Vout = Av \times Vin$ and dividing both sides by *Av* gives:

$$Vin = \frac{Vout}{Av}$$

$$Vin = \frac{300mV}{125}$$

$$Vin = 2.4mV$$

Using peak-peak, peak and RMS values in gain calculations
When performing voltage (or current) gain calculations, it doesn't matter whether peak-to-peak, peak or RMS values are used as long as you use only one type throughout the calculation. For example, don't use an RMS value of input voltage and a peak value of output voltage when calculating the gain. If you do your answer will be wrong.

Calculating current and power gain
The current gain and power gain of an amplifier can be calculated using the equations:

$$\boxed{Ai = \frac{Iout}{Iin}}$$

Where:
Ai is the current gain (as a ratio)
Iin is the input current (in amps)
Iout is the output current (in amps)

$$\boxed{Ap = \frac{Pout}{Pin}}$$

Where:
Ap is the power gain (as a ratio)
Pin is the input power (in watts)
Pout is the output power (in watts)

Practise using the gain equations for yourself by trying the following questions.

1. What is the voltage gain of an amplifier with 175mVpp on the input and 7Vpp on the output?
   40

2. What is the voltage gain of an amplifier with 500mV$_{RMS}$ on the input and 16Vp on the output? **Tip:** Be careful with this question.
   32

3. What is the current gain of an amplifier with 600µAp into the input and 1.25Ap out of the output?
   2083.3

4. What is the power gain of an amplifier with 50mW on the input and 200W on the output?

4000

5. What is the voltage at the output of an amplifier with a voltage gain of 75 and 650mVp-p on the input?

48.75 VOLTS

6. What is the current out of an amplifier with a current gain of 5 and an input current of 0.5A?

2.5 AMPS

7. What is the power dissipated by the load of an amplifier with a power gain of 5000 and an input power of 5mW?

25 WATTS

8. What is the input voltage of an amplifier with a voltage gain of 90 and an output voltage 900mV?

0.01 VOLTS

9. What is the input current of an amplifier with a current gain of 17 and an output current of 2.3A?

0.1353 AMPS

= 135.3 mA

10. What is the input power to an amplifier with a power gain of 175 and 15W being dissipated by its load?

0.08571 WATTS

Amplifier input-output phase relationship

The input and output signals of amplifiers are often in phase with each other as shown in Figure 8 below.

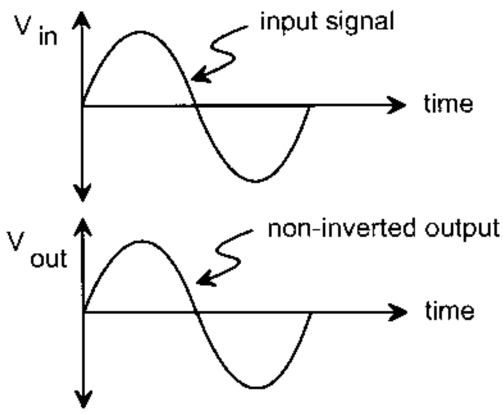


Figure 8 *An amplifier can input and output signals that are in phase with each other*

But often the output is inverted (that is, upside-down) relative to the input as shown in Figure 9 below.

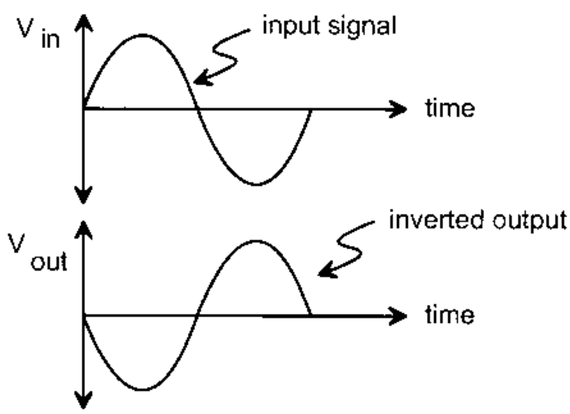


Figure 9 *An amplifier can have an output signal that is inverted relative to its input*

To denote the phase inversion, a minus sign is put in front of the gain value (when the gain is expressed as a ratio). For example, an amplifier with a gain of -20 (minus 20) means that the amplifier produces an output that is 20 times bigger and inverted.

Distortion

An important thing to appreciate about amplifiers is that the voltage and current of the input signal is not transferred to the amplifier's output. As already mentioned, what amplifier's do is take the power supply's voltage and current and shape it into an output that is a copy of the input.

In that sense, an amplifier is a bit like a photocopier - You put an A4 page onto the platen (the glass surface that is scanned), press the copy button and, a short time later, the copier outputs an A4 piece of paper with an image on it that is a copy of the original page. The copy was made from paper already inside the machine and nothing of the original piece of paper is used to make the new piece of paper.

The photocopier analogy is a good way to understand amplifiers because it helps you to understand a limitation of all amplifiers. As you probably already know, the copy from a photocopier is never as good as the original; if you compare the pair using a magnifying glass or microscope, there is always some small imperfection in the copy. In the same way, the output of amplifiers is never exactly the same as the original; there is always some small difference between the two.

A word you've probably heard of before is "distortion" which is the act of using a force to change the shape of something so that it's no-longer the correct shape. This word is used with amplifiers to describe the differences between the input signal (ie the original signal), and the output signal (the copy). All amplifier output signals consist of some amount of distortion. This distortion can be undetectable to the ear, but it's always present.

That said, there are amplifiers that intentionally introduce distortion. The most common example of this would be the distortion box for an electric guitar. However, for most amplifiers, distortion is undesirable and ideally there shouldn't be any (that is, the distortion figure would be 0%). A typical distortion figure for an amplifier in a hi-fi system is about 0.1% but this figure can vary from system to system.

[As an aside, "hi-fi" is an abbreviation and contraction of the words *high fidelity*. Fidelity is another word for faithful. Hi-fi amplifier's have a relatively low distortion and so produce a relatively faithful copy of the original signal.]

Overdriving amplifiers

If an amplifier's output signal derived from the power supply's voltage, it stands to reason that the output signal can't be bigger than the power supply's voltage. Figure 10 below shows what would happen if you made the input signal too big for the amplifier's gain (or the amplifier's gain too big for the input signal) and attempted to make an output signal that is bigger than the power supply voltage.

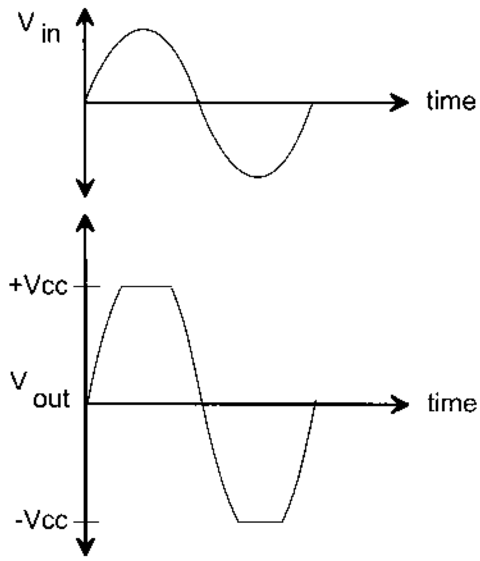


Figure 10 *An example of a problem called "clipping"*

As the positive peaks of the output signal attempt to exceed the *+Vcc*, they get chopped off. Similarly, as the negative peaks attempted to exceed the *-Vcc*, they get chopped off too. This effect is called *clipping* and, when this happens, the signal source is said to be *overdriving* the amplifier.

Obviously, the shape of the output signal (the copy) is no-longer the same shape as the input signal so clipping is a type of distortion.

Cascaded amplifiers

It is common practice with small signal amplifiers to connect them in series; that is, the output of one amplifier is connected to the input of another (see Figure 11). Amplifiers connected in this way are referred to as *cascaded amplifiers* and are made from two or more individual amplifier *stages.*

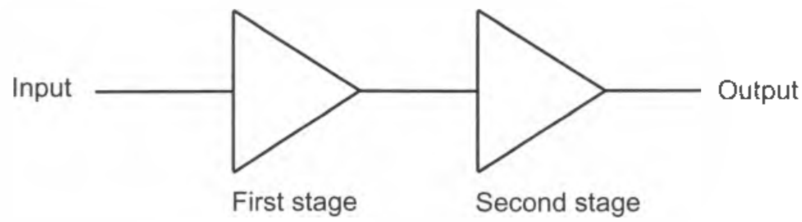


Figure 11 *Two amplifiers connected in series to form a cascaded amplifier*

The overall voltage gain of a cascaded amplifier is the product of the gain of all amplifier stages. Expressed mathematically, the overall voltage gain of the cascaded amplifier in Figure 8 above is:

$$\boxed{Av_{(T)} = Av_{(1)} \times Av_{(2)}}$$

Let's do an example. What is the voltage gain of the cascaded amplifier in Figure 11 if the first stage's gain is 100 and the second stage's gain is 2?

$$Av_{(T)} = Av_{(1)} \times Av_{(2)}$$

$$Av_{(T)} = 100 \times 2$$

$$Av_{(T)} = 200$$

To prove that the total gain of the combined amplifier stages is 200, Let's solve the same question by assuming an input voltage of 10mV and calculating the output voltage. First, we would need to calculate the first stage's output voltage:

$$Vout_{(1)} = Av_{(1)} \times Vin_{(1)}$$

$$Vout_{(1)} = 100 \times 10mV$$

$$Vout_{(1)} = 1V$$

$Vout_{(1)}$ now becomes the input voltage to the second stage which has a gain of 2. So, the second stage's output voltage is:

$$Vout_{(2)} = Av_{(2)} \times Vin_{(2)}$$

$$Vout_{(2)} = 2 \times 1V$$

$$Vout_{(2)} = 2V$$

For an input voltage of 10mV, the output voltage of the second stage is 2V. So, the cascaded amplifier's voltage gain is:

$$Av_{(T)} = \frac{Vout_{(2)}}{Vin_{(1)}}$$

$$Av_{(T)} = \frac{2V}{10mV}$$

$$Av_{(T)} = 200$$

Let's do another example. What is the voltage gain of the cascaded amplifier in Figure 12?

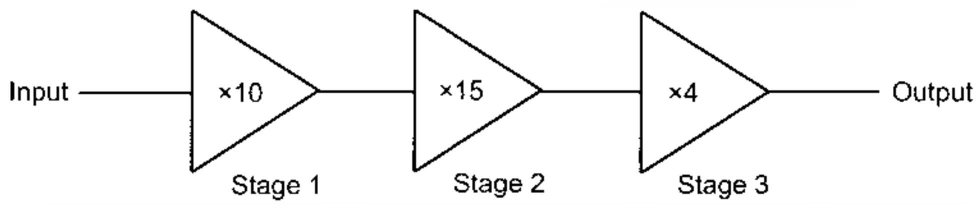


Figure 12 *A cascaded amplifier made from three amplifier stages*

$$Av_{(T)} = Av_{(1)} \times Av_{(2)} \times Av_{(3)}$$

$$Av_{(T)} = 10 \times 15 \times 4$$

$$Av_{(T)} = 600$$

Practise calculating the gain of cascaded amplifiers for yourself by trying the following questions.

1. What is the voltage gain of a three-stage cascaded amplifier with the following stage gains: Stage 1 = 25; Stage 2 = 12; and Stage 3 = 9?

2. What is the voltage gain of a two-stage cascaded amplifier with the following stage gains: Stage 1 = 39 and Stage 2 = -55?

3. Is the output of the amplifier in the question above in phase with the amplifier's input or is it inverted?

4. What is the voltage gain of a two-stage cascaded amplifier with the following stage gains: Stage 1 = -65 and Stage 2 = -33?

5. Is the output of the amplifier in the question above in phase with the amplifier's input or is it inverted?

6. What's the gain of the second stage in Figure 13 below?

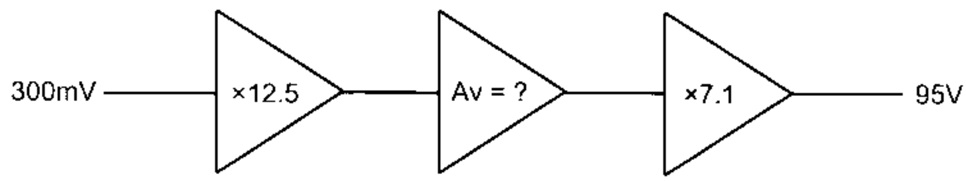


Figure 13

Measuring amplifier voltage gain

A common method used by technicians to test an amplifier involves measuring its actual voltage gain and comparing it to its specified or theoretical voltage gain. If they are the same or similar, the amplifier is probably working. If they're different, the amplifier may be faulty.

To measure an amplifier's voltage gain, it must be made to amplify an appropriate test signal. The sinewave is ideal for this purpose (though other waveshapes are better for testing other amplifier performance characteristics). The sinewave from a function generator or signal generator is usually adequate.

As the amplifier's input and output signals must be measured to determine its gain, a CRO is also needed. Figure 14 below shows how the signal generator and CRO are connected to the amplifier.

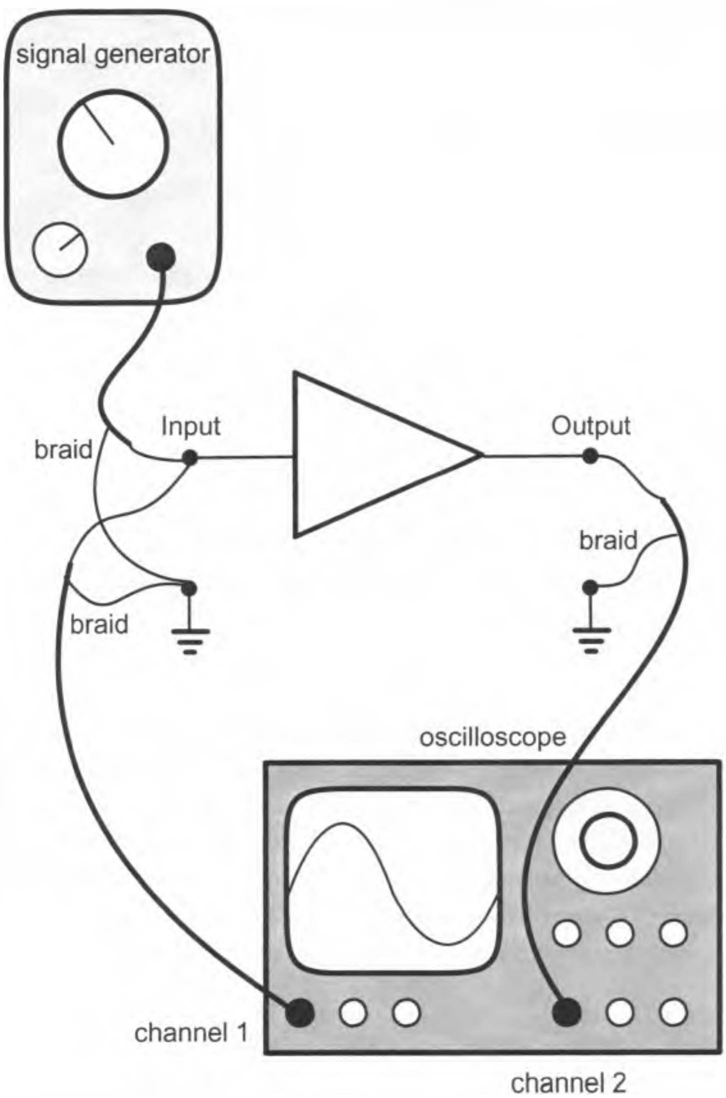


Figure 14 *The electrical connections necessary for measuring an amplifier's voltage gain with a CRO*

Care must be taken when doing practical exercises at TAFE because our CRO leads have two alligator clips, one red and one black. The red clip connects to the input or output. The black clip connects to the circuit common. You'll know that you've likely connected the leads correctly if all black clips connect to the same point in the circuit. If not, something is wrong.

Once these connections are made, the testing procedure is as follows:

1. Adjust the CRO to observe both the amplifier's input and output signals.

2. Adjust the signal generator for a sinewave with a frequency in the amplifier's mid-band region.

   Note: For now, set the frequency to 1kHz. The issue of amplifier mid-band region is explained later in this workbook.

3. Adjust the signal generator so that the input signal is not overdriving the amplifier (that is, the amplifier's output is not clipped).

4. Measure the amplifier's peak-to-peak input voltage (*Vin*).

5. Measure the amplifier's peak-to-peak output voltage (*Vout*).

6. Use the measured values of *Vin* and *Vout* to calculate the "measured" gain using: $Av = \frac{Vout}{Vin}$.

7. Compare the input and output signals and if the output is inverted add a minus sign to the gain figure.

Can I use peak values for the input and output voltages?
Yes, but it's easier to measure peak-to-peak values of a signal when using a CRO so you're probably better off using them instead.

Can I use a digital multimeter to measure the input and output voltages?
Usually, no. There are three problems with using digital multimeters. First, they wont tell you whether the output signal is clipped. Second, they won't tell you whether the out signal is inverted (which you need to know so that you can add the minus sign to the gain figure). And third, digital multimeters can only measure the voltage of AC signals below a certain frequency (typically around 600Hz but some can go higher) so if you test using the wrong frequency, you'll obtain an incorrect gain figure. CROs can typically measure frequencies up to at least 15MHz.

Words that may be new to you

Amplifier	A device or circuit that produces an output voltage, current or power that is (usually) bigger than the input.
Amplification	Occurs when the output voltage, current or power is bigger that the input.
Attenuation	Occurs when the output voltage, current or power of a circuit is smaller than the input (this is the opposite of amplification).
Amplifier stage	One of several individual amplifiers that makes up a cascaded amplifier.
Black-box	A way of looking at circuits when we only want to know what happens at its output if an input is applied and we don't care what is inside the circuit or how it works.
Cascaded amplifier	An amplifier made from several amplifiers connected in series.
Clipping	A type of distortion where the tops and bottoms of the output signal are chopped off.
Distortion	The undesirable changes introduced to an output voltage or current by an amplifier.
Driving	When a circuit provides voltage or current to a load.
Gain	The ratio of an amplifier's output voltage to its input voltage.
Inverted output signal	An output voltage or current that is upside down compared to the original input signal.
Load	Any device or circuit that is connected to the output of another circuit.

Over-driving	The condition when the size of the input signal causes the amplifier's output to clip.
Phase Relationship	The expression used to describe whether the input and output signals of an amplifier are in-phase, out of phase or phase-inverted.
Signal source	Any device or circuit that produces a voltage or current that can be used as an input to another circuit.
Small signal amplifier	An amplifier designed to amplify voltages below approximately 1V.
Stage	An individual amplifier circuit in a cascaded amplifier.
Stage gain	The gain of an individual amplifier stage in a cascaded amplifier.

Skill practice 1

Practise measuring the voltage gain of single stage and multistage (cascaded) amplifier circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Op amp cascaded amplifier panel (using ninv. and inv. stages)
- digital multimeter (DMM)
- two BNC to alligator-clip leads
- two BNC to RCA plug leads
- banana leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	Control measures:
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ____________________ ____________________ ____________________	Move bags and other objects from walkways Plan lifting of equipment Other: ____________________ ____________________ ____________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ____________________ Date: ____________________

2. Read the following note.

   For this activity you will be working with a cascaded amplifier that has already been made for you and consists of two individual amplifier stages. Each amplifier stage is made from an amplifier inside an integrated circuit (IC). For now, you don't need to know how these ICs work. However, you do need to understand what the circuit is doing at the block diagram level. Figure 1 shows this.

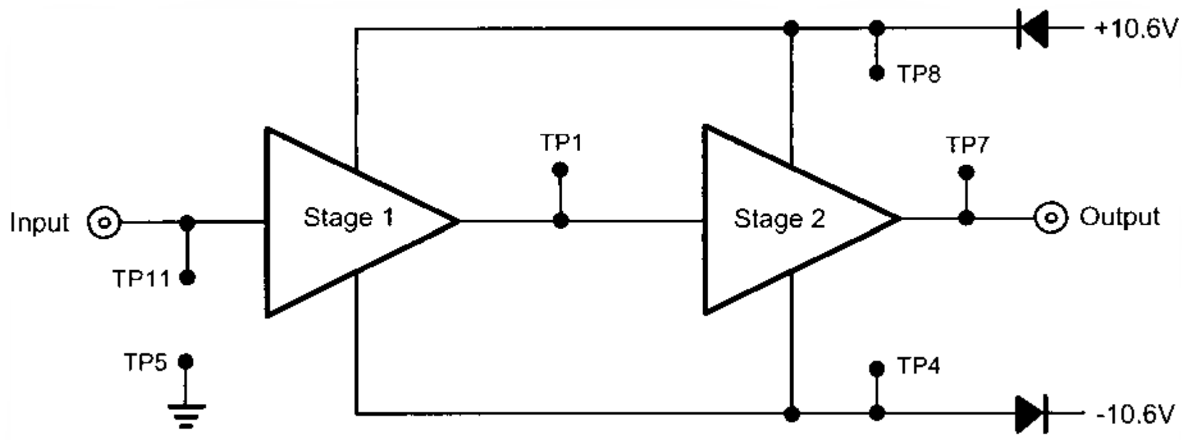


Figure 1

3. Gather the equipment needed for this exercise.

4. If you're in one of rooms L1-18, L2-05 or L2-12 set the **tracking/independent** control on the bench-mounted DC Power Supply so that the unit is in **tracking** mode.

5. If you're in one of rooms L1-12, L1-18 or L2-03 adjust the DC Power Supply's **series/parallel** controls so that the unit is in **series** mode.

6. Now vary the voltage on the right-hand side power supply. You'll notice that the voltage meter for both left and right side outputs varies. If they don't call the teacher.

   Note: To explain what you're doing, the controls for the right-side power supply output now controls both power supply outputs. So, the right-side supply is said to be the **Master** and the left-side supply the **Slave**.

7. Adjust the master voltage control so that both outputs are 10.6V. Check this with the digital multimeter (DMM).

8. Turn the power supply OFF.

9. Connect the positive terminal of the master output to the *+10V* socket on the panel. Connect the negative terminal of the slave output to the *-10V* socket on the panel. Connect the negative terminal of the master output to the *0V* socket on the panel.

The teacher needs to check your work at this point...

10. When the teacher has checked your set-up, turn on the power supply.

11. Locate TP5 on the amplifier panel. This test point will be your 0V reference point (or common) for all your voltage measurements. In other words, the digital multimeter's black probe (and the CRO lead's black alligator-clip) must be connected to TP5 when making all measurements.

12. Check that TP4 is -10V and TP8 is +10V with respect to common using the digital multimeter (DMM).

13. If there is no voltage on either one of these test points then turn off the power supply and call the teacher.

14. Adjust the bench-mounted signal generator's output for a 1kHz sinewave.

15. Connect the signal generator to the *Signal In* socket on the amplifier panel with a BNC-to-RCA lead.

16. Connect the CRO's channel 1 to the input of the first amplifier stage (**TP11**) as shown in Figure 2 below.

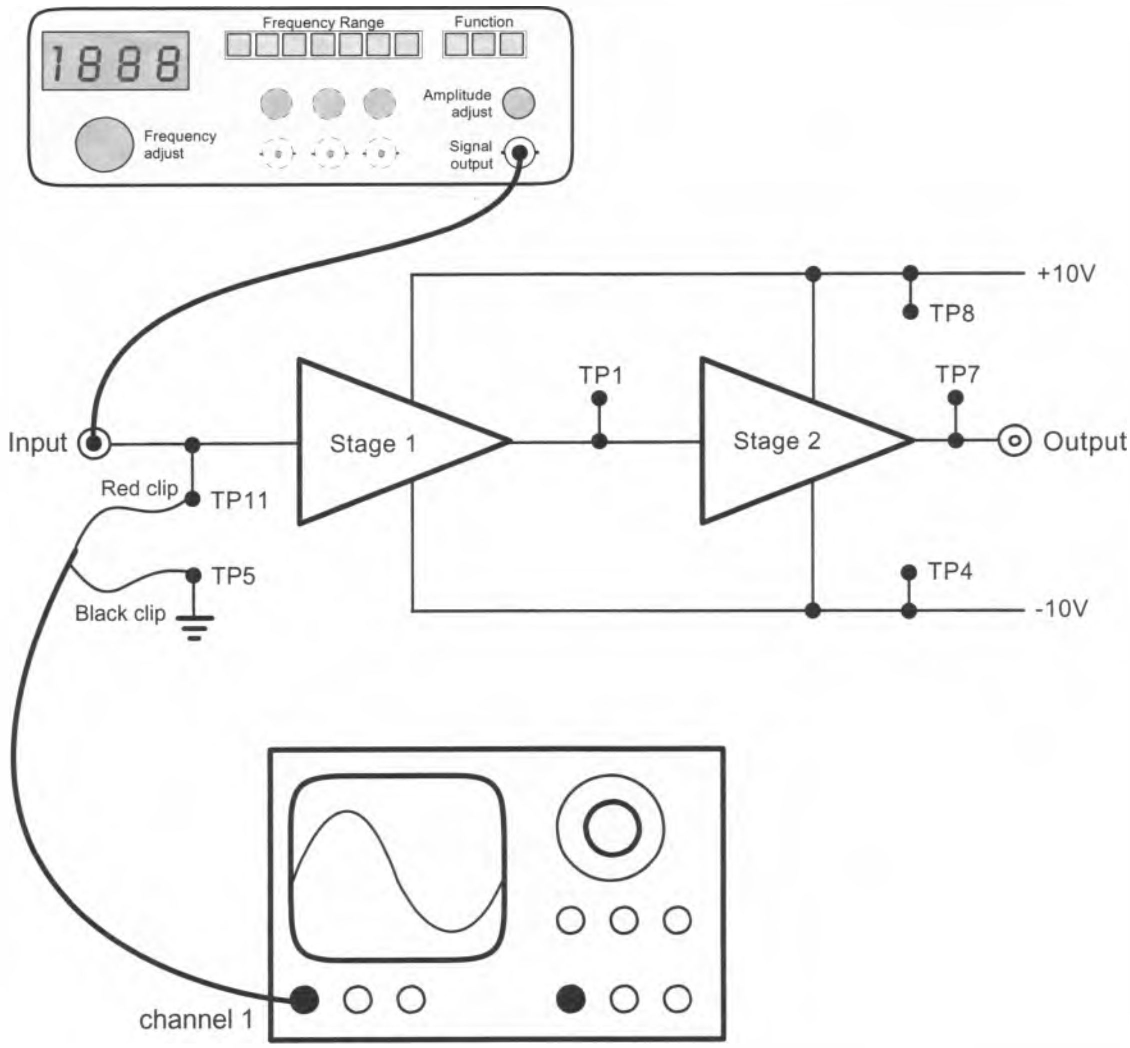


Figure 2

17. Adjust the CRO to view channel 1.

18. Set the amplifier's input voltage to 200mVp-p.

19. Connect the CRO's channel 2 to the output of the first amplifier stage (**TP1**) as shown in Figure 3 on the next page.

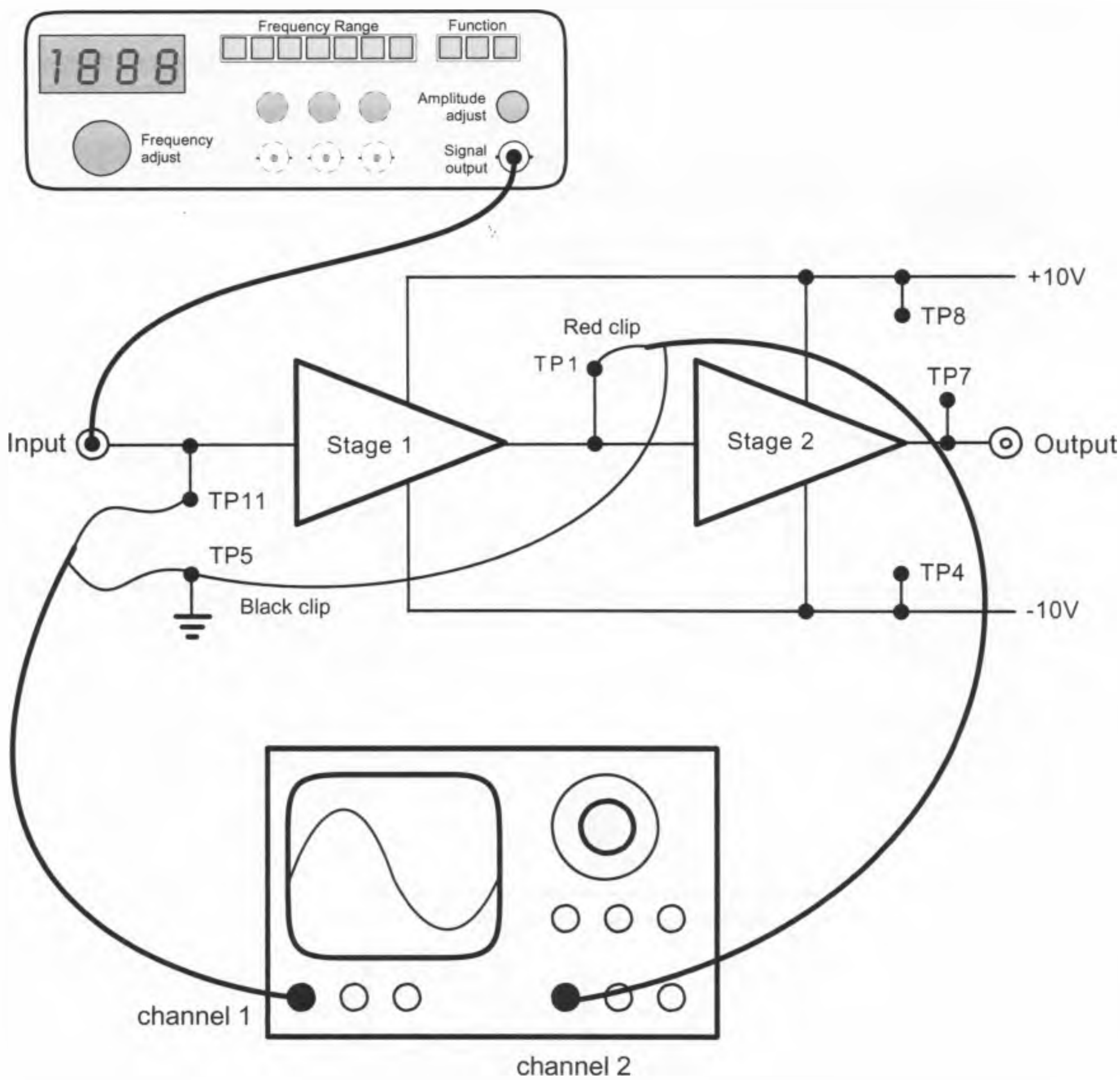


Figure 3

20. Adjust the CRO to display both channels.

21. Measure the first stage's output voltage. Record the value in Table 1 (on the next page).

22. Note and record the phase relationship between the two signals.

23. Calculate and record the first stage's voltage gain using the equation: $Av = \frac{Vout}{Vin}$.

Table 1

Stage 1			
Vin (TP11) (See Step 18)	**Vout (TP1)** (See Step 21)	**Phase relationship** (See Step 22)	**Av** (See Step 23)
200mVp-p	4 V	OUT	20

The teacher needs to check your work at this point...

24. Connect the CRO's channel 1 to the input of the second amplifier stage (**TP1**) and its channel 2 to the output of the second amplifier stage (**TP7**) as shown in Figure 4 below.

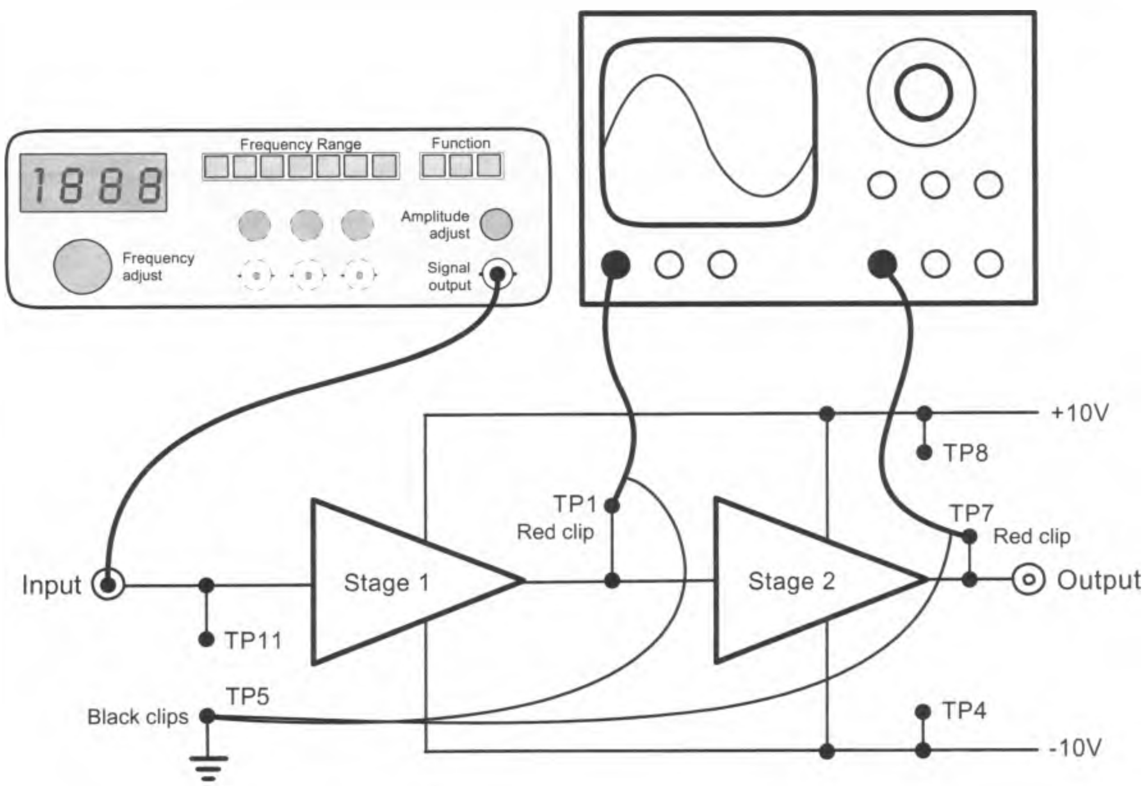


Figure 4

25. Measure the second stage's input and output voltages. Record your measurements in Table 2 below.

26. Note and record the phase relationship between the two signals.

27. Calculate and record the second stage's voltage gain.

Table 2

Stage 2			
Vin (TP1)	**Vout (TP7)**	**Phase relationship**	**Av**

Question 1
What extra piece of information must you add to the gain value you calculated in Step 27 to indicate there is a phase inversion between the input and the output signals?

The teacher needs to check your work at this point...

28. Connect the CRO's channel 1 to the input of the first amplifier stage (**TP11**) as shown in Figure 5 below.

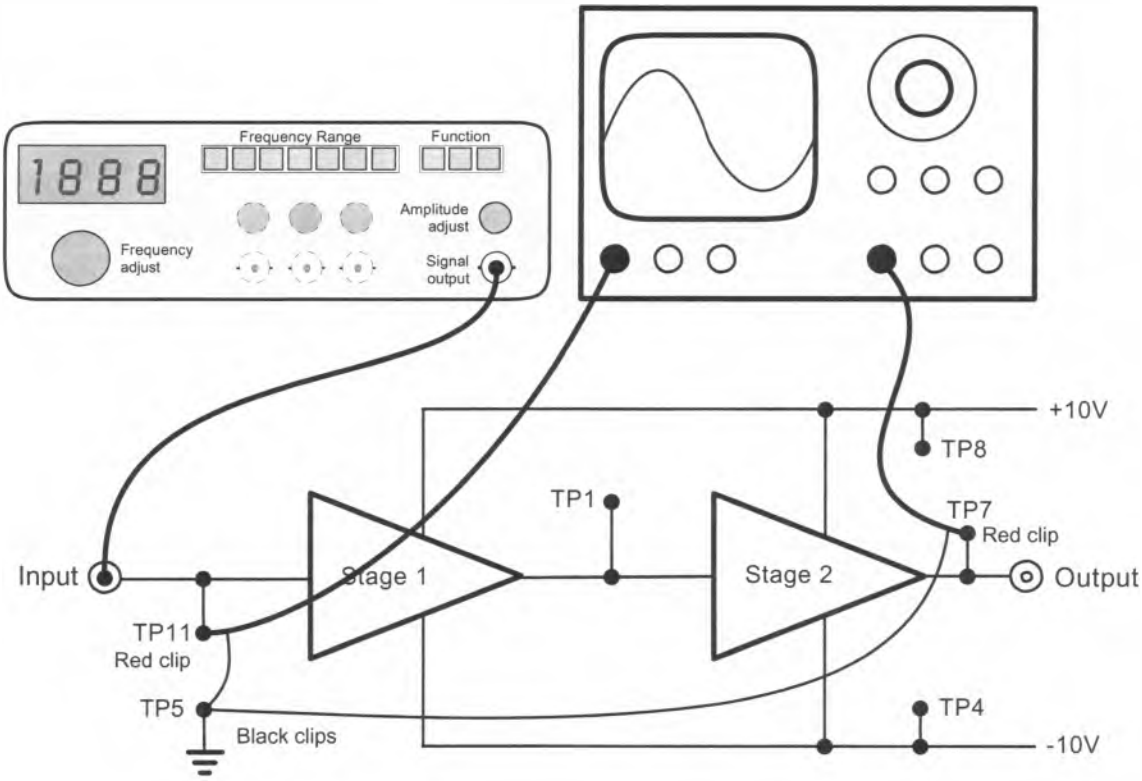


Figure 5

29. Measure the cascaded amplifier's input and output voltages. Record your measurements in Table 2 below.

30. Note and record the phase relationship between the two signals.

31. Calculate and record the cascaded amplifier's voltage gain.

Table 3

Cascaded amplifier			
Vin (TP11)	**Vout** (TP7)	**Phase relationship**	**Av**

Question 3
Calculate the cascaded amplifier's voltage gain using the individual stage gain values you calculated in Steps 21 and 25 (see Tables 1 and 2).

Question 4
Compare the value that you just calculated for Question 3 with the measured value of gain that you calculated in Step 29. What might explain any differences?

The teacher needs to check your work at this point...

32. While observing the output voltage on the CRO, switch off the DC power supply and note what happens.

Question 5
Why wasn't the amplifier able to produce an output voltage when the DC power supply was turned off?

33. Turn the DC power supply back on.

34. While observing the output voltage, slowly increase the amplifier's input voltage until you see the tops and/or the bottoms of the output signal begin to be chopped off. (If this doesn't happen, call the teacher.)

Question 6
What is the name for this type of distortion?

____

____

Question 7
Why does increasing the input voltage cause this type of distortion to occur?

____

____

____

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. Draw the general symbol for an amplifier.

2. On the above diagram show and label the input, output and power supply connections.

3. Why must all amplifiers be connected to a DC power supply?

____

____

____

4. Indicate which of the following devices would most likely be connected to the input or output of an amplifier:

(a) microphone ____________________

(b) speaker ____________________

(c) signal generator ____________________

(d) 5 watt resistor ____________________

(e) another amp ____________________

(f) tape deck ____________________

5. What is the voltage gain of an amplifier with a 10mV signal on its input and an 850mV signal on its output?

6. What is the output voltage of an amplifier with an input signal of 100mV and a gain of 40?

7. What value of input voltage is needed to produce 3V at the output of an amplifier with a gain of 120?

8. What is the current gain of an amplifier with an output current of 500mA and an input current of 2mA?

9. An amplifier has an input signal of 1V at 20μA and delivers 2A into an 8 ohm load. What is the amplifier's power gain? (**Tip:** calculate the input and output powers first.)

10. An amplifier has a sinewave input of 50mV RMS at 3kHz and a gain of 20. Draw two cycles of the output waveform on the axes provided. Label all relevant voltage and time values on your diagram.

11. An amplifier has a gain of -10. What does the negative sign mean?

12. What is the voltage gain of an amplifier with an input voltage of 20mV RMS and an output of 15V peak-to-peak?

13. What is the voltage gain of a three-stage cascaded amplifier with the following stage gains: Stage 1 = 10; Stage 2 = 5; and Stage 3 = 15?

14. What is the voltage gain of a three-stage cascaded amplifier with the following stage gains: Stage 1 = -7; Stage 2 = 13; and Stage 3 = -4?

15. Is the output of the amplifier in the question above in phase with the amplifier's input or is it inverted? Explain your answer.

Section 2 Gain expressed in decibels

Purpose

To develop your ability to specify and interpret the gain performance of small signal amplifiers (and other devices) in decibels.

Objectives

Once you have completed this section you should be able to:

- Calculate the voltage/current/power gain of an amplifier in decibels
- Determine either the input or output voltage/current/power of an amplifier given its gain as a decibel and the output or input voltage/current/power
- Calculate the total gain of a cascaded amplifier in decibels
- Explain the significance of negative decibel values
- Use an oscilloscope to measure the voltage gain of commercially available domestic hi-fi amplifiers

Introduction

The previous section introduced to the concept of gain and how to determine it by measurement. This section extends on this a little to show you how to specify and interpret gains expressed in decibels.

Gain expressed in decibels

It is common in electronics to express gain (amplification) and losses (attenuation) of power in decibels (dB) instead of as a ratio. There are two key reasons for this:

- Decibels are a logarithmic representation of ratio and are useful when working with sound because the hearing response of our ears is logarithmic.

- It easier to find the total gain/loss of a system made up of several circuits having gains and/or losses.

To explain this first point, our hearing is not linear. That is, if you halve the energy used to make a sound, it wont sound half as loud. In fact, you'd barely hear the difference. To make a sound half as loud, the energy used to make it must be decreased by a factor of 10.

Putting this into electrical terms, 100mW of sound is twice as loud as 10mW which in turn is only twice as load as 1mW.

When you think about it, logarithmic properties are tricky things. For example, is an increase of 9mW of power significant or not? The answer to the question depends on your starting point. If the original sound was 1mW then an increase of 9mW to 10mW is significant. However, if the original sound was 100mW then an increase of 9mW to 109mW is insignificant.

Using decibels gets around this problem by producing numbers for logarithmic properties that are meaningful regardless of your starting point.

Importantly, the use of decibels is so common that most manufacturers specify the gain or loss introduced by their systems in decibels. That being the case, technicians need to be familiar with using them.

Bels

When comparing two values of power (such as *Pout* and *Pin* of an amplifier) the way that we have done this so far is as a simple ratio. That is, power gain (A_P) = $\frac{Pout}{Pin}$. For example, if the power out of an amplifier is 125W and the power in is 125mW then:

$$A_P = \frac{125W}{125mW}$$

$$A_P = 1,000$$

The number 1,000 is a ratio that tells us that the output power is a thousand times bigger than the input power. To express this value in Bels (B), it is simply "logged" using the *Log* button on your calculator. So, using the same example:

$$\text{Power gain in Bels } A_{P(B)} = Log\frac{Pout}{Pin}$$

$$= Log\frac{125W}{125mW}$$

$$= Log\ 1,000$$

$$= 3B$$

Decibels
The Bel is a very large a unit of measurement. In fact, it's too large for specifying the gain of amplifiers and is a little bit like using a metre ruler to measure the length of an ant. For this reason, decibels (dB) are used instead. A decibel is one tenth of a Bel. Or put another way, there are 10 decibels in a Bel.

So power gain expressed in decibels is calculated using the equation:

$$\boxed{Ap_{(dB)} = 10Log\frac{Pout}{Pin}}$$

Continuing the previous example, the power gain in decibels is:

$$\text{Power gain in dB } Ap_{(B)} = 10Log\frac{Pout}{Pin}$$

$$= 10Log\frac{125W}{125mW}$$

$$= 10 \times 3$$

$$= 30dB$$

Let's do another example. An amplifier has an input power of 1mW with 50mW being dissipated by the load. What is the amplifier's power gain in decibels?

$$Ap_{(B)} = 10Log\frac{Pout}{Pin}$$

$$= 10Log\frac{50mW}{1mW}$$

$$= 10Log50$$

$$= 10 \times 1.6989$$

$$= 17dB$$

As a technician, you're expected to be able to take an amplifier with a specified gain in decibels and calculate either its output for a given input or its input for a given output. The following examples show this is done.

Example 1: An amplifier with a power gain of 33dB has an input power of 100mW. What is the power dissipated by the load?

In this example we can't use the equation $A_P = 10Log\frac{Pout}{Pin}$ as it is. This is because we already have the amplifier's power gain in decibels. We want to find *Pout* so the equation must be transposed to make *Pout* the subject.

$Ap = 10Log\frac{Pout}{Pin}$ dividing both sides by 10 gives:

$\frac{Ap}{10} = Log\frac{Pout}{Pin}$ anti-logging both sides gives:

$Log^{-1}\left(\frac{Ap}{10}\right) = \frac{Pout}{Pin}$ multiplying both sides by *Pin* gives:

$Pin \times \left[Log^{-1}\left(\frac{Ap}{10}\right)\right] = Pout$ then, rewriting the equation gives:

$$Pout = Pin\left[Log^{-1}\left(\frac{Ap}{10}\right)\right]$$

Now we can find *Pout*:

$$Pout = 100mW \times \left[Log^{-1}\left(\frac{33dB}{10}\right)\right]$$

$$= 100mW \times [Log^{-1}3.3]$$

$$= 100mW \times 1,995$$

$$= 199.5W$$

Example 2: An amplifier with a power gain of 60dB has a load that is dissipating 30W. What is the power into the amplifier?

Again, we can't use the equation $A_P = 10Log\frac{Pout}{Pin}$ as it is. To find *Pin*, the equation must be transposed to make *Pin* the subject.

$$Ap = 10Log\frac{Pout}{Pin}$$ dividing both sides by 10 gives:

$$\frac{Ap}{10} = Log\frac{Pout}{Pin}$$ anti-logging both sides gives:

$$Log^{-1}\left(\frac{Ap}{10}\right) = \frac{Pout}{Pin}$$ reciprocating both sides gives:

$$\frac{1}{Log^{-1}\left(\frac{Ap}{10}\right)} = \frac{Pin}{Pout}$$ multiplying both sides by *Pout* gives:

$$\frac{Pout}{Log^{-1}\left(\frac{Ap}{10}\right)} = Pin$$ then, rewriting the equation gives:

$$Pin = \frac{Pout}{Log^{-1}\left(\frac{Ap}{10}\right)}$$

Now we can find *Pin*:

$$Pin = \frac{Pout}{Log^{-1}\left(\frac{Ap}{10}\right)}$$

$$= \frac{30W}{Log^{-1}\left(\frac{60dB}{10}\right)}$$

$$= \frac{30W}{Log^{-1}6}$$

$$= \frac{30W}{1,000,000}$$

$$= 30\mu W$$

Practise using and converting power gain in decibels by trying the following questions for yourself.

1. What is the power gain in decibels of an amplifier with an input power of 50mW and an output power of 200W?

2. What is the power gain in decibels of an amplifier with an input power of 600mW and an output power of 600mW?

3. What is the power gain in decibels of an amplifier with an input power of 1.5W and an output power of 900mW?

4. What is the power dissipated by the load (that is, the output power) of an amplifier with a power gain of 37dB and an input power of 5mW?

5. What is the power into an amplifier with a power gain of 22.4dB and 15W being dissipated by its load?

Questions 2 and 3 on the previous page highlight a couple of interesting issues with gains expressed in decibels. First, a gain of 1 (neither amplification nor attenuation) is 0dB. Second, gains of less than 1 (attenuation or loss) convert to negative decibels.

On this second issue, an important point of difference must be emphasised. Recall that the negative sign in front of a gain expressed as a ratio denotes phase inversion. However, the negative sign in front of a gain expressed as a decibel denotes attenuation instead of amplification.

Voltages and currents in decibels

The voltage and current gain of an amplifier may also be stated in decibels. However, the equation is different.

$$Av_{(dB)} = 20Log\frac{Vout}{Vin}$$

$$Ai_{(dB)} = 20Log\frac{Iout}{Iin}$$

Let's do an example. An amplifier has an input voltage of 10mV and an output voltage of 2V. What is the voltage gain in decibels?

$$Av_{(dB)} = 20Log\frac{Vout}{Vin}$$

$$= 20Log\frac{2V}{10mV}$$

$$= 20Log200$$

$$= 20 \times 2.301$$

$$= 46dB$$

Notice that we use *20Log* rather than *10Log* for the calculation of voltage and current gain in decibels. This is explained shortly.

First, practise using these equations for yourself by trying the following questions.

1. What is the voltage gain of an amplifier in decibels with 175mVp-p on the input and 7Vp-p at the output?

___

___

2. What is the current gain of an amplifier in decibels with 600µA in and 1.25A out?

___

___

3. What is the voltage at the output of an amplifier with a voltage gain of 37.5dB and 650mVp-p on the input?

4. What is the current out of an amplifier with a current gain of 14dB and an input current of 0.5A?

5. What is the voltage on the input of an amplifier with a voltage gain of 39dB and an output voltage 900mV?

6. What is the current into an amplifier with a current gain of 24.6dB and an output current of 2.3A?

Why *20Log* instead of *10Log*?

Using *20Log* instead of *10Log* is odd when you think about it. Recall that the point of multiplying the logged power gain by ten is to convert it to the metric sub-multiple "deci" (giving decibels instead of Bels). So why multiply the logged voltage gain by twenty instead?

To answer this question, the equation $A_{V(dB)} = 20Log\frac{V_{OUT}}{V_{IN}}$ needs to be rewritten as: $A_{V(dB)} = 2 \times 10Log\frac{V_{OUT}}{V_{IN}}$. The two equations give exactly the same answer but the second shows that we're still multiplying the logged gain by ten to convert it to decibels. That being the case, the real question is: Why are voltage and current gains expressed in decibels multiplied by two?

To answer this, you must first appreciate that signals in communications systems ultimately connect to transducers such as antennae or speakers. Importantly, it's not the voltage or the current alone that determines the strength of the transmitted signal or the sound level out of the speaker, it's both of them together. In other words, it's the power. So, power gains and losses are usually the main focus of communications systems.

That said, it's much easier to measure voltage or current than it is to measure power. (As a case in point, have you ever measured power?) So, it's common practice to measure changes in voltage or current and use this information to infer the size of the change in power.

The trouble is, when a change in output voltage or current occurs, the resulting change in power is greater. To prove this, consider the simple example below. As the maths show, the power dissipated by the resistor in Figure 1a is 10W. In Figure 1b, the voltage has dropped by 10% however the power has dropped by 19%!

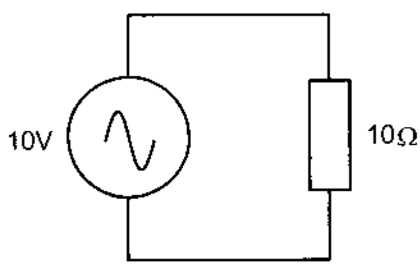


Figure 1a

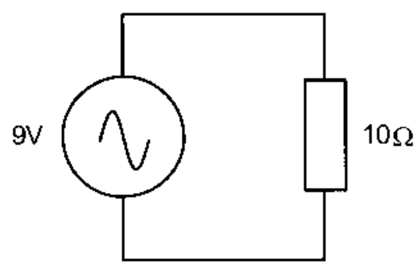


Figure 1b

$$P_R = \frac{V^2}{R}$$

$$P_R = \frac{10V^2}{10\Omega}$$

$$P_R = 10W$$

$$P_R = \frac{V^2}{R}$$

$$P_R = \frac{9V^2}{10\Omega}$$

$$P_R = 8.1W$$

Complicating the matter further, changes in power are not directly proportional to changes in voltage or current. To prove this point, Table 1 below shows the changes in supply voltage for Figure 1 in 1V steps and the corresponding changes in the power. Notice that every 1V change is an additional change of 10% of the original voltage (10V) but the size of the power change (relative to the original power of 10W) is different each time.

Table 1

Supply voltage	Change in supply	Resistor power	Change in power
10V	N/A	10W	N/A
9V	10%	8.1W	19%
8V	20%	6.4W	36%
7V	30%	4.9W	51%
6V	40%	3.6W	64%
5V	50%	2.5W	75%
4V	60%	1.6W	84%
3V	70%	0.9W	91%
2V	80%	0.4W	96%
1V	90%	0.1W	99%

These two issues are a little inconvenient if we want to infer the size of a power change by using changes in voltage or current that caused it.

To get around this problem, when voltage and current gains of amplifiers (and other devices) are converted to decibels, *20Log* is used instead of *10Log*. This small change to the equation works neatly as a correction factor that produces the same decibel value regardless of whether we're using voltage, current or power.

Calculating the gain in decibels of cascaded amplifiers

The previous section introduced you to the concept of cascaded amplifiers and showed how to calculate their total gain. The example of the cascaded amplifier in Figure 2 below was used to demonstrate how this is done. As the maths below show, the total gain of the arrangement is 600.

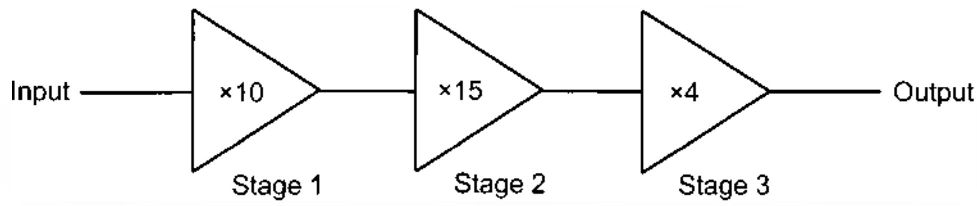


Figure 2 *Cascaded amplifier made from three amplifier stages*

$$Av_{(T)} = Av_{(1)} \times Av_{(2)} \times Av_{(3)}$$

$$Av_{(T)} = 10 \times 15 \times 4$$

$$Av_{(T)} = 600$$

When the total gain of a cascaded amplifier and the gain of the individual amplifier stages are expressed in decibels it's easy to understand the other main reason for using decibels.

The total gain in decibels is:

$$Av_{(dB)} = 20Log600$$

$$Av_{(dB)} = 55.7dB$$

And the individual stage gains are:

$$Av_{1(dB)} = 20Log10 \qquad Av_{2(dB)} = 20Log15 \qquad Av_{3(dB)} = 20Log4$$

$$Av_{1(dB)} = 20dB \qquad Av_{2(dB)} = 23.5dB \qquad Av_{3(dB)} = 12dB$$

Now, do you see any connection between the individual stage gains in decibels and the entire amplifier's gain?

You probably noticed that the total gain in decibels is the sum of the individual stage gains in decibels. In other words:

$$Av_{(T)(dB)} = Av_{(1)(dB)} + Av_{(2)(dB)} + Av_{(3)(dB)}$$

$$Av_{(T)(dB)} = 20dB + 23.5dB + 12dB$$

$$Av_{(T)(dB)} = 55.5dB$$

From this example you can see that is easier to find the total gain of a cascaded amplifier given the individual stage gains in decibels rather than as ratios. All you need do is add the values up instead of multiplying them.

Practise calculating the gain of cascaded amplifiers in decibels by trying the following questions yourself.

1. What is the voltage gain (in decibels) of a three stage cascaded amplifier with the following stage gains: Stage 1 = 34.2dB; Stage 2 = 19.6dB; and Stage 3 = 7.7dB?

2. What is the voltage on the output of a two stage cascaded amplifier with stage gains of 18dB and 31dB and an input voltage of 15mVp-p?

3. What is the voltage on the input of a two stage cascaded amplifier with stage gains of 12dB and 25dB and an output voltage of 18Vp-p?

Decibels used as a unit of measurement

Decibels are sometimes used as a unit of measurement. For example, sound level figures are expressed in decibels. However, as decibels are really just another way of expressing ratios, this is problematic. To explain, if we say that the sound level of normal conversation is 60dB, the question begs: 60dB bigger than what? In other words, what's the reference?

In the case of sound, the reference is a thing known as *the threshold of hearing*. This is the quietest sound that can possibly be heard by the average human. In other cases where decibels are used as a unit of measurement, a reference has usually been internationally agreed to and a letter is added to dB to denote this. The following lists and explains some examples.

- **dBm**

  This is used when power levels expressed in decibels are compared to a standard power level of 1mW. A given power may be greater than or less than 1mW and therefore will have a + or - dBm value.

- **dBW**

  Similar to dBm except 1W is used as the reference.

- **dBV**

  Similar to dBm but 1V is used as the reference.

- **dBu**

  This is a measure of how much bigger or smaller a voltage is compared to the voltage necessary to make a 600Ω load dissipate 1mW.

- **dBr**

  Some texts and diagrams use the abbreviation dBr. Where this appears, it means that a power level at a given point in a system is being compared to a previously defined power level (often the input power to the system). dBr is therefore a specific statement that the power level at that point is so many decibels *relative* to the previously defined power level.

Words that may be new to you

Bel	A unit of measurement that is simply the logarithm of a ratio.
Decibel	One tenth of a Bel.
dB	The abbreviation for decibel.

Student notes

Skill practice 2

Practise measuring the voltage gain of commercial available domestic hi-fi amplifiers

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- stereo amplifier (Sherwood)
- one RCA to alligator-clip lead
- three BNC to alligator-clip leads

WARNING:
This exercise involves working with equipment that connects to mains.
Under no circumstances are you to open the unit.

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	Control measures:
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ______________________ ______________________ ______________________	Move bags and other objects from walkways Plan lifting of equipment Other: ______________________ ______________________ ______________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ______________________ Date: ____________________

2. Read the following notes.

Background
Before proceeding with the exercise it's worth briefly discussing the way the volume control works. Technicians tend to call this control the gain control because it's a more accurate description of what it does. The volume control effectively varies the amplifier's gain.

Figure 1 below shows one of the ways that this is commonly done. As you can see, the input signal is connected to an amplifier with a fixed gain via a potentiometer.

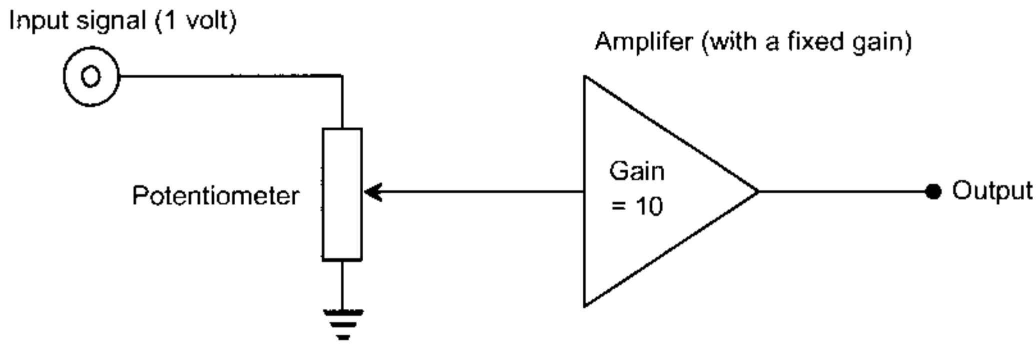


Figure 1

The potentiometer acts as voltage divider. When the pot's wiper is at the top, all of the input signal (typically 1V RMS) is passed to the amplifier and appears as 10V at the output. When the pot's wiper is at some point lower down the pot, only a sample of the input signal is passed to the amplifier. When the wiper is at the bottom, no signal is fed to the amplifier because its input is effectively grounded.

Interestingly, this means that the gain control can be adjusted so that the amplifier amplifies an input signal or attenuates it. The idea that an amplifier attenuates signals might seem outrageous at first, however, there's method in the madness.

To explain, the voltage out of a CD player or tape deck is typically 1V RMS which produces 125mW at the output of a power amplifier connected to an 8Ω load. In terms of loudness, this will produce about the same volume of sound as two people talking. So, if you want the music in the room to be quieter than two people talking (say, because you're studying for a TAFE exam...), the amplifier must attenuate the input signal's voltage!

Working safely

For this exercise you're going to practise measuring gain. To do so, you'll be working with a commercially manufactured amplifier so you must exercise extreme care. To avoid electrocution and damage to the amplifier follow the procedure and call the teacher to check your work when instructed.

Also, if things don't seem to be happening the way you think they should, switch the amplifier off immediately and call the teacher. Finally, throughout the exercise take extreme care NOT to short any of the output speaker leads other as this will destroy the amplifier's output stage instantly.

> **WARNING:**
> To avoid damaging the amplifier, follow this procedure very carefully.

3. Make sure the amplifier is switched off and that it's **NOT** plugged into mains.

4. Turn on the bench-mounted signal generator and adjust its frequency controls for a 200Hz sinewave output.

5. Set the signal generator's amplitude control to the middle of its travel.

6. Activate the signal generator's *-20dB attenuation* control.

7. Connect an RCA to alligator-clip lead to the amplifier's right $\boxed{R}$ channel AUX IN RCA socket.

8. Use a BNC to alligator-clip lead to connect the lead that you connected in Step 5 to the signal generator's output.

   Note: Once this is done, you have an input signal connected to the amplifier.

9. Connect Channel 1 of the CRO to the amplifier's input signal using another BNC to alligator-clip lead.

10. Connect Channel 2 of the CRO to the right $\boxed{R}$ channel of the amplifier's $\boxed{A}$ set of speaker outputs using the third BNC to alligator-clip lead.

    Note 1: Take extreme care with this Step. The alligator-clips must be connected to the correct output terminals - That is, Red-to-Red and Black-to-Black.

    Note 2: Take special care to ensure the alligator clips cannot touch each other (which would short the amplifier's output and destroy the amplifier's output stage).

11. Turn on the CRO and adjust it so that it displays the input signal and is ready to display the output signal.

12. Measure the input signal's amplitude.

    Note: The input signal should be less than 2Vp-p. If it's much bigger than this, the signal generator's *-20dB attenuation* control has not been activated.

The teacher needs to check your work at this point...

13. Once the teacher has checked your set-up, plug the amplifier into mains and turn it on.

14. Select the AUX input option.

15. Adjust the input signal's amplitude down to 200mVp-p.

16. Adjust the amplifier's volume control to setting number 32.

17. Check that the amplifier has an output signal and that it is bigger than the input signal. If not, turn off the amplifier **immediately** and call the teacher.

18. Press the amplifier's *Balance* button.

    Note: When you do this the display will read "BAL #" (where # is a number). Check that the number is 0. If not, use the amplifier's up/down buttons to set it to zero.

19. Press the amplifier's *Tone* button once.

    Note: When you do this the display will read "BASS #". Set the amplifier's *Bass* control to 0 if it's not already.

20. Press the amplifier's *Tone* button again.

    Note: When you do this the display will read "TRBL #". Set the amplifier's *Treble* control to 0 if it's not already.

21. Measure the amplifier's output voltage and record this in Table 1 below next to *Volume Setting 32* in the AUX input column.

22. Calculate and record the amplifier's voltage gain in decibels.

23. Set the volume control to maximum or until the output signal starts clipping (whichever happens first).

24. Measure and record the new output voltage then calculate and record the amplifier's new voltage gain in decibels.

25. Adjust the volume control to setting number 5 and repeat step 24.

    Note: There will be an output signal but you'll have to adjust the CRO's Channel 2 *Vertical Attenuation* control all the way down to the *10mV/div* position to see it.

Table 1

Volume Setting	Vout (AUX)	Gain (dB) (AUX)
5		
32		
Max		

Question 1
Which of the three volume settings attenuates the input signal instead of amplifying it?

Question 2
Why would a domestic hi-fi amplifier attenuate an input signal? **Tip:** If you're not sure, read the background notes on page 2-21.

Question 3
When adjusting the volume control, why does the amplifier's output voltage change in small steps instead of in a continuous motion as you might expect?

____

____

____

26. Find the volume control setting that gives the amplifier a 0dB voltage gain.

Tip: What's a gain of 0dB as a ratio?

Volume setting for 0dB = _______________

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. What is the power gain in decibels of an amplifier with an input power of 5mW and an output of 10W?

2. What is the output power of an amplifier with a gain of 63dB and an input power of 150μW?

3. What is the maximum input voltage for an amplifier with a voltage gain of 45dB and a maximum output voltage of 40Vp-p?

4. What will happen to the output signal if the input signal exceeds this maximum voltage?

5. A three stage cascaded amplifier has the following voltage gains, $Av_{(1)} = 10$, $Av_{(2)} = 15$, $Av_{(3)} = 20$. Convert the amplifier's stage gains into decibels.

6. What is this cascaded amplifier's voltage gain in decibels?

7. What is this cascaded amplifier's voltage gain as a ratio?

8. Convert the following values specified in decibels to power and voltage gains (as ratios).

dB	**Power gain**	**Voltage gain**
3dB		
6dB		
20db		
-3dB		
-13dB		
-29db		

9. What does the negative sign in front of a value in decibels mean?

Student notes

Section 3 Amplifier frequency response

Purpose To develop your ability to perform frequency response tests on amplifiers.

Objectives Once you have completed this section you should be able to:

- Explain the terms *frequency response* and *bandwidth*
- Calculate the output voltage of an amplifier at the lower and upper frequency roll-off points for a given input voltage and gain
- Describe a procedure for measuring the frequency response of an amplifier
- Use an oscilloscope to measure and graph the frequency response of amplifier circuits

Introduction

So far, you have looked at the voltage gain of amplifiers expressed both as a ratio and in decibels. Gain is obviously an important amplifier parameter that service technicians must know about. Another is bandwidth. Poor bandwidth performance in amplifiers can mean that the signal reproduced at the output is not a good copy of the signal on the input. In terms of hi-fi and communications equipment, this would mean that the sound is not nearly as good as it should be. In this section we'll look at what bandwidth is and learn how to measure it for any amplifier.

What is frequency response?

You have probably found in your experience that, in terms of your overall comfort, there is a range of temperatures between which you feel most comfortable. For example, any day with temperatures between 20°C and 26°C might be perfect; not too hot and not too cold. However, as temperatures drop below 20°C and or rise above 26°C you might find yourself getting too cold or too hot. And, as the temperatures drop a lot below 20°C (say -5°C) or rise a lot above 26°C (say 45°C) you get extremely uncomfortable. If we drew a graph of your comfort versus temperature it might look something like:

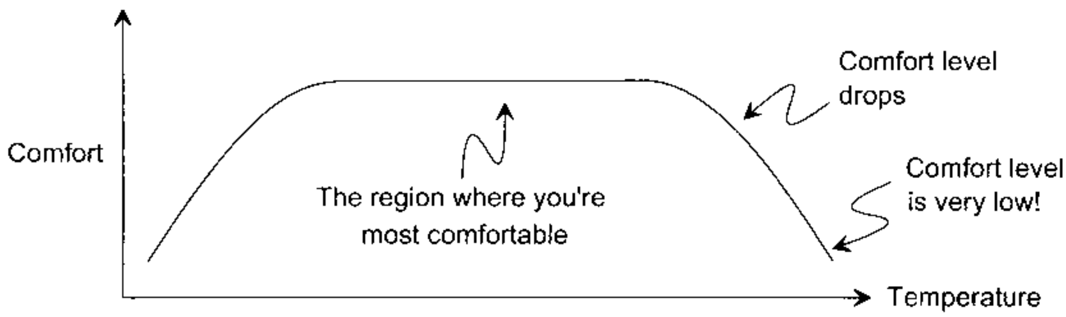


Figure 1 *The graph of temperature versus comfort*

In the same way, there is usually a range of frequencies over which the gain of any amplifier is what it is supposed to be. Within this range the amplifier will usually have the same value of gain. Outside of this range the amplifier's gain will start to drop-off and may even go below 1 (that is, not amplifying at all but attenuating the signal instead).

If we graph an amplifier's gain performance over a range of frequencies the graph would look like either Figure 2a or 2b.

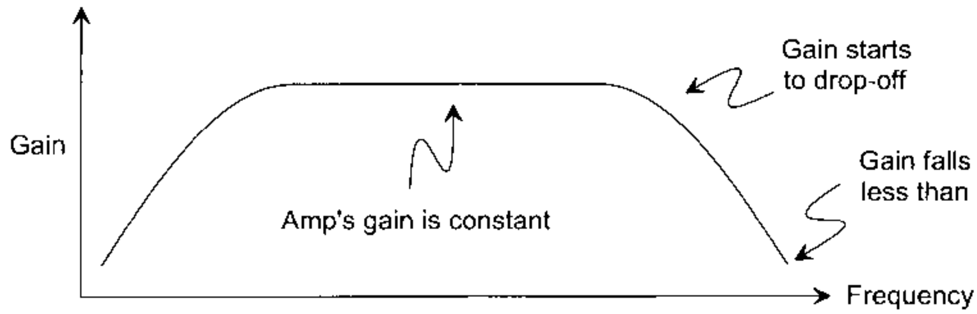


Figure 2a *The frequency response of a domestic hi-fi*

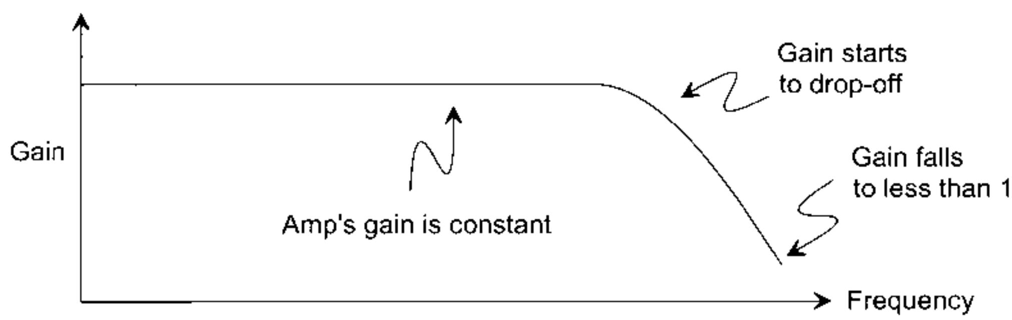


Figure 2b *The frequency response of operational amplifiers*

How the amplifier performs over a wide variety of frequencies is known as its *frequency response.*

Why is the frequency response of amplifiers the way it is?
The natural limitations of electronic components like transistors is one important factor that gives us the responses shown in Figure 2. However, often the bandwidth of an amplifier is deliberately designed to perform in a particular way so design considerations are another important factor.

Bandwidth

It's usually important when designing and testing amplifiers to ensure that they can amplify signals over an acceptable range of frequencies. For example, amplifiers designed to accurately reproduce audio signals such as music should be able to amplify all the frequencies in the music that we humans can hear (typically 20Hz to 20kHz but this varies a little from person to person).

A quantitative measure of an amplifier's frequency performance (and other circuits such as filters) that is widely used is called *bandwidth*. As its name implies the bandwidth of an amplifier is the frequency width of the band over which the amplifier's gain is maximum and fairly constant (or *flat*).

However, given the gain performance of amplifiers gently begins to drop-off, the trick to such a measure is to have precise points where we all agree that the gain has changed sufficiently to no-longer be part of the bandwidth. Two points that most manufacturers, engineers and technicians use are called the lower and upper frequency roll-off points and are said to occur where the gain (or output voltage) has dropped to 70.7% (or 0.707) of the gain (or output voltage) in the flat part of the response.

Showing this on a graph with some numbers, an amplifier's frequency response might look like that shown in Figure 3 below.

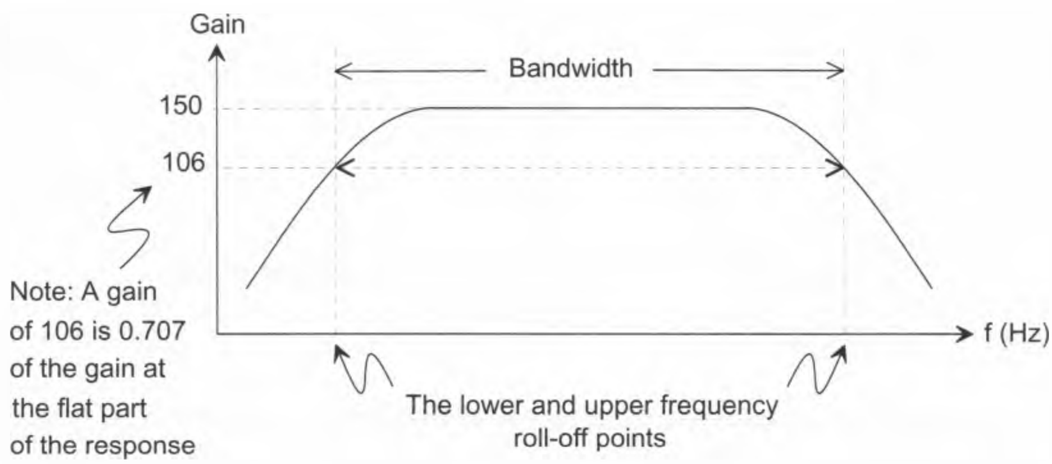


Figure 3 *The frequency response of an amplifier showing the bandwidth*

Choosing 0.707 of the flat part of the response's output voltage as the threshold points for the lower and upper frequency roll-off points might seem odd given the gain is allowed to drop so much. However, 0.707 is significant because it's the point at which the human ear can start to notice the difference in loudness. So, in fact, the choice is a good one; we wouldn't notice a change in loudness before it dropped to 0.707 anyway.

[**Note:** It's purely a coincidence that this figure is the same as the correction factor used to convert a peak AC values to RMS.]

Common terms used when talking about amplifier frequency response

There are many terms used to describe the various parts of the frequency response graph of an amplifier. Figure 4 below shows some examples.

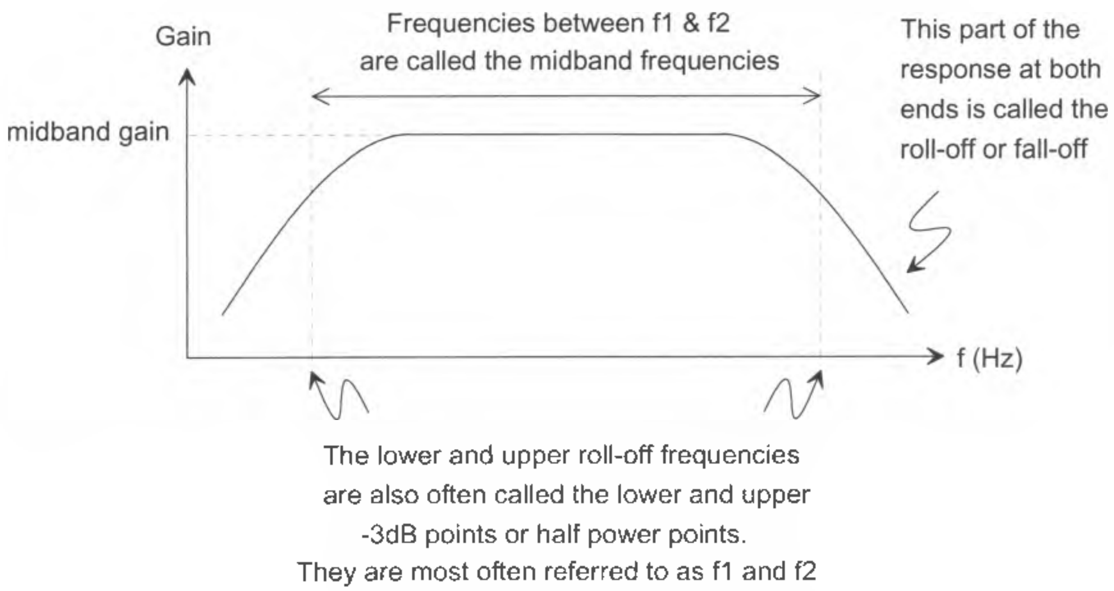


Figure 4 *Terms frequently used with frequency response graphs*

Most of the terms need little or no explanation as they are just different ways of saying the same thing. However, the terms *-3dB points* and *half-power points* may need some explanation.

Why are *f1* and *f2* called the -3dB points?

Consider the frequency response graph in Figure 5 below.

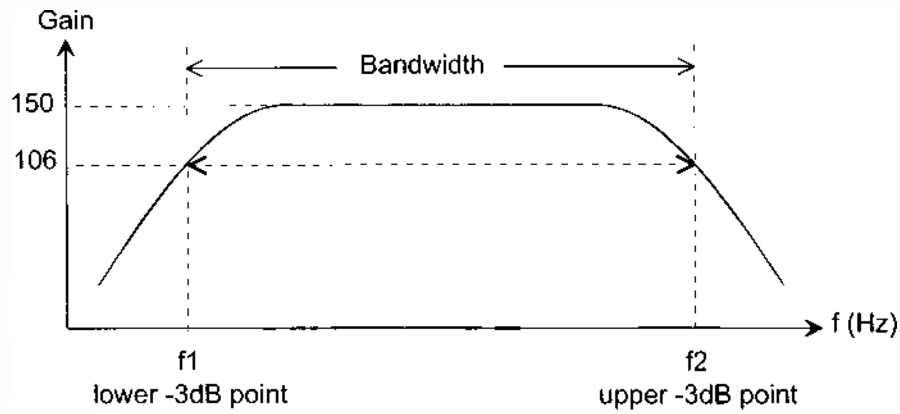


Figure 5 *Frequency response of an amplifier*

If we calculate the gain in decibels for the midband frequencies and at *f1* and *f2* we get:

$Av_{(dB)}$ at the midband	$Av_{(dB)}$ at *f1* and *f2*
$Av_{(dB)} = 20LogAv$	$Av_{(dB)} = 20LogAv$
$Av_{(dB)} = 20Log150$	$Av_{(dB)} = 20Log106$
$Av_{(dB)} = 43.5dB$	$Av_{(dB)} = 40.5dB$

When we compare these two gains we can see that there is a 3dB difference between them. Specifically, the gain at *f1* and *f2* is 3dB less than the gain at the midband and hence these two points are called the -3dB points.

Why are *f1* and *f2* called the half-power points?

The lower and upper frequency roll-off points are often called the half power points because, when the output voltage has dropped to 0.707 of the maximum output voltage, the power has dropped by half. Here's mathematical proof using a simple series resistive circuit:

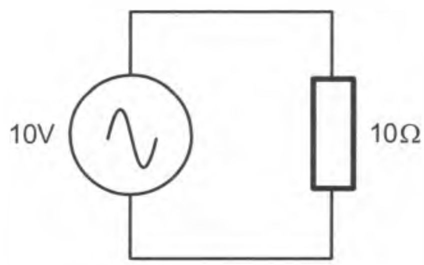


Figure 6a

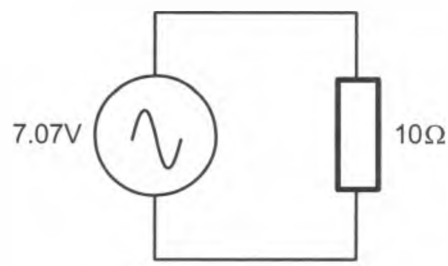


Figure 6b

The power in this resistor is:

$$P_R = \frac{V^2}{R}$$

$$P_R = \frac{10V^2}{10\Omega}$$

$$P_R = 10W$$

The power in this resistor is:

$$P_R = \frac{V^2}{R}$$

$$P_R = \frac{7.07V^2}{10\Omega}$$

$$P_R = 5W$$

Note how, even though the supply voltage has only dropped from 10V (in Figure 6a) to 7.07V (in Figure 6b), the power has dropped from 10W to 5W.

Measuring the frequency response of amplifiers

As a technician you will be expected to be able to find the frequency response of an amplifier by measurement. The procedure is as follows:

- Connect the CRO's channel 1 input to the amplifier's input and the channel 2 input to the amplifier's output.
- Connect a sinewave generator to the amplifier's input (your set-up should now look like Figure 7 below).

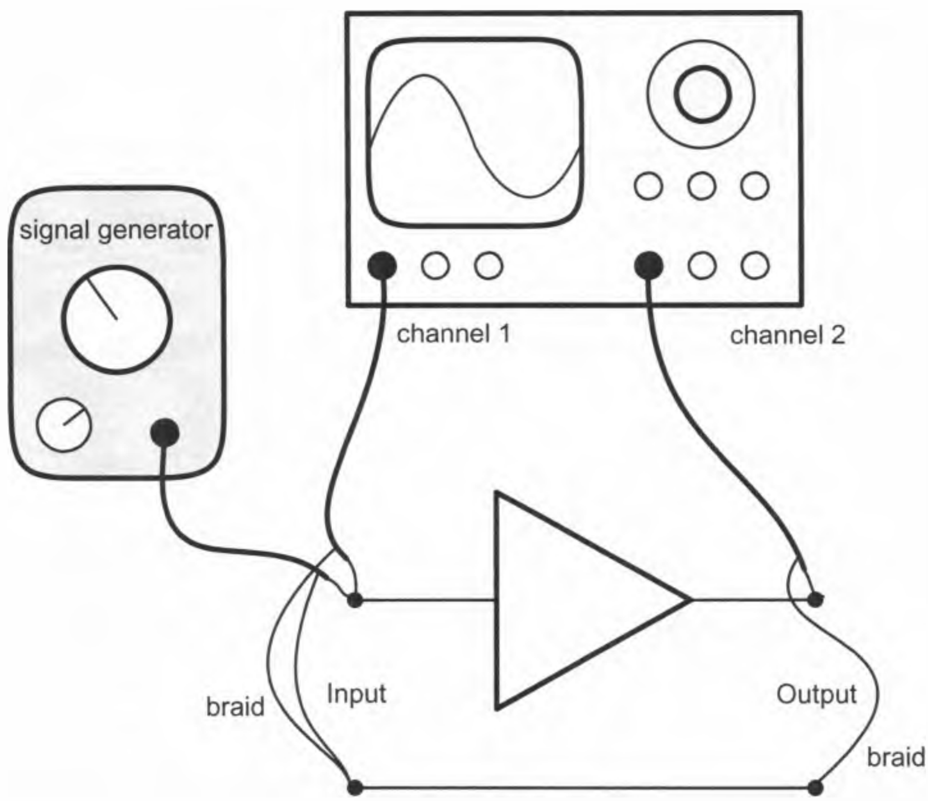


Figure 7 *The test arrangement for measuring frequency response*

- Adjust the input signal's amplitude so that the amplifier's output signal isn't clipping.
- Measure the amplifier's input voltage.
- Measure the amplifier's output voltage.
- Calculate the amplifier's gain as a ratio (and convert to decibels if appropriate).
- Repeat for several frequencies (for example, at 500Hz, 1kHz, 2kHz and so on).
- Plot the results on a graph of frequency versus gain (or frequency versus output voltage).

Let's do a quick example on paper. The table below shows the measured output voltages of an amplifier with an input voltage of 100mVp-p at 500Hz, 1kHz, 5kHz, 10kHz, 20kHz and 50kHz. The gain at each frequency has also been calculated (in decibels).

Frequency	**Vout**	**Gain** (in dB)
500Hz	179mVp-p	5dB
1kHz	1.79Vp-p	25dB
5kHz	5.62Vp-p	35dB
10kHz	5.62Vp-p	35dB
20kHz	1.41Vp-p	23dB
50kHz	126mVp-p	2dB

Then, plotting these values on a graph of frequency versus gain and drawing the *line of best fit* gives the graph in Figure 8 below.

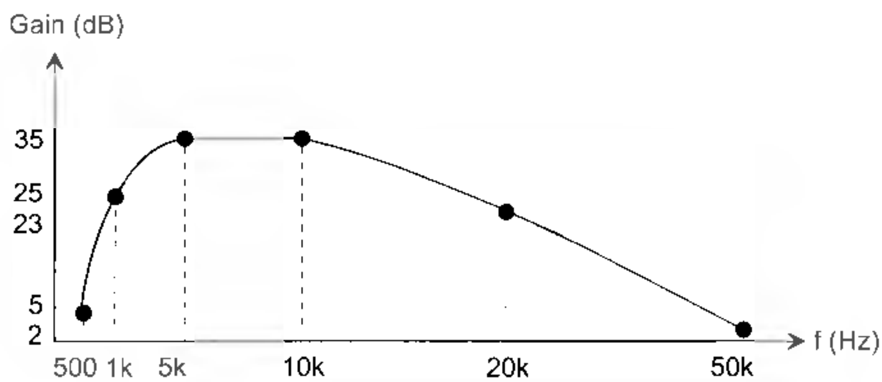


Figure 8 *A graph of frequency response using the gain values in the table above*

If you look at Figure 8 closely, you'll notice that the graph looks different to the frequency response of typical amplifiers. The roll-off's slope seems to be different at each end of the frequency spectrum (steep at the lower end and shallow at the upper end). However, the frequency response of typical amplifiers has a roll-off at each end of the frequency spectrum with the same slope (see Figure 2a on page 3-3 for an example).

The reason the graph in Figure 8 is different is because it shows how the graph would look if it were drawn on graph paper that is linear in both axes (like the kinds of graph paper that you've seen and used before). However, doing so actually misrepresents the amplifier's frequency performance because, although the roll-off's slope is the same at both ends of the spectrum, the frequencies are much bigger at the upper end relative to the lower end.

To correct for this visual illusion the frequency response of amplifiers (and filters) must be drawn on graph paper that has the lower frequencies spaced out but the higher frequencies closer together. Such graph paper is called log/linear graph paper and an example is shown in Figure 9.

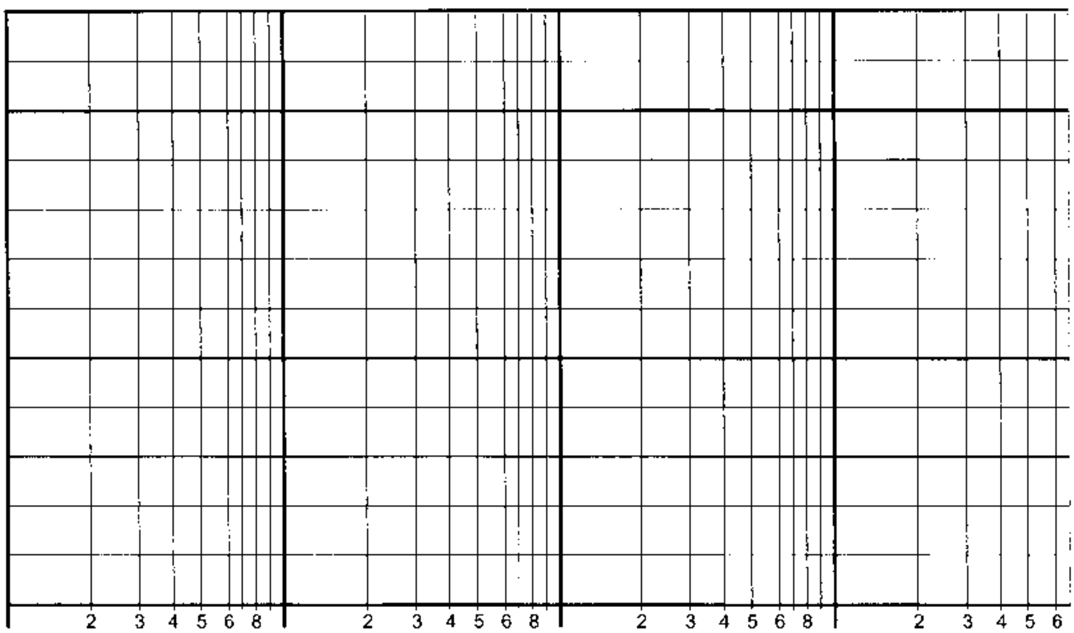


Figure 9 *A sample of log/lin graph paper*

This kind of graph paper gets its name because the vertical axis is linear like normal graph paper with evenly spaced lines. However, on the horizontal axis, the lines get closer together as the numbers get bigger in a logarithmic fashion with the pattern repeating every count of 10 (referred to as a decade).

This kind of graph paper is a little more tricky to use than conventional graph paper. The vertical axis is used to represent gain values and is set up just like normal graph paper. The horizontal axis is used to represent frequency. Although numbers are written across the bottom or the top of the paper, you will have do assign the decade value (that is, whether the "1" is 1Hz or 10Hz or 100Hz and so on).

Once you have set up the graph with your values, you find the vertical line that represents the frequency you measured and place a mark on the horizontal line that represents the gain you measured at that frequency. If you're not sure about this don't worry. You'll be doing a lot of this in the practical exercises to get you used to it.

At how many frequencies should I measure the gain?

Once the procedure for measuring the frequency response of an amplifier is understood, the questions that immediately arise are: At how many frequencies should the amplifier's gain be measured? And, what frequencies should be used?

If you don't measure the amplifier's gain at enough frequencies the graph will be inaccurate. But if you measure the gain at too many frequencies you may waste time. Similarly, you could make gain measurements at twelve or so frequencies (which would be about right) but, if you use the wrong frequencies, the graph would be incomplete. To help you develop your skills in this area, the following discussion provides an approach that you can use.

To help decide how many gain measurements are enough, consider the diagram in Figure 10 below. As you can see, the response of an amplifier is pretty flat over a wide range of frequencies (the midband frequencies). That being the case, there is usually not much point measuring the gain at many frequencies in this region. Three or four would be enough.

However, at the beginning of the roll-off at each end of the response, the amplifier's gain changes quite a bit over a small range of frequencies so it makes sense to make three or four gain measurements in these regions. Then, beyond the lower and upper frequency roll-off points the response changes at a constant rate so only one or two gain measurements need to be made in these parts of the response . This means that you would need to make about sixteen gain measurements altogether. With practise you can obtain almost exactly the same graph with as few as 9 to 12 measurements.

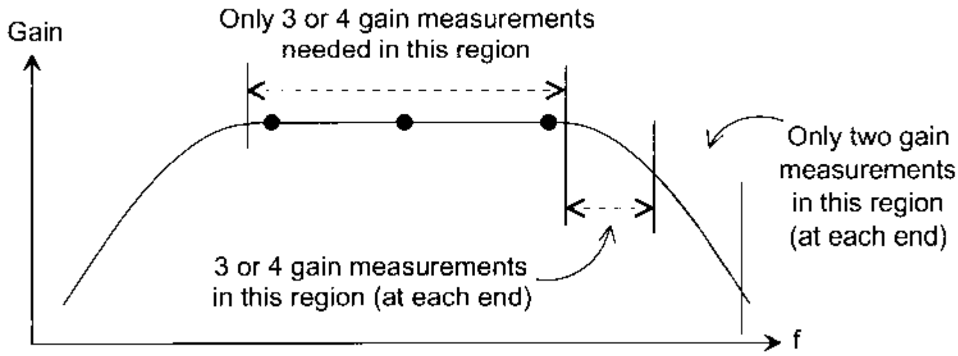


Figure 10 *The points at which the gain should be measured when making a frequency response graph*

Deciding which frequencies to use is a little more tricky and knowing a little bit about the amplifier that you're testing helps.

The first step is to find a midband frequency (it doesn't matter which one). To do this, sweep through the frequencies on your signal source (keeping the input voltage constant) until you find a range of frequencies where the output voltage doesn't change. When you have, you've just found the midband region because a constant output voltage must mean a constant gain. So, calculate and record the gain at this frequency (see Figure 11).

This step can be made faster if you know what the amplifier you're testing is used for. For example, if you are testing a telecommunications repeater you would know that the *f1* is 300Hz and the *f2* 3500Hz. Or, if you are testing an audio amplifier then you know the *f1* is about 20Hz and the *f2* is about 20kHz. In these two examples, you could start your testing at 1kHz because 1kHz falls between 300Hz - 3500Hz and 20Hz - 20kHz.

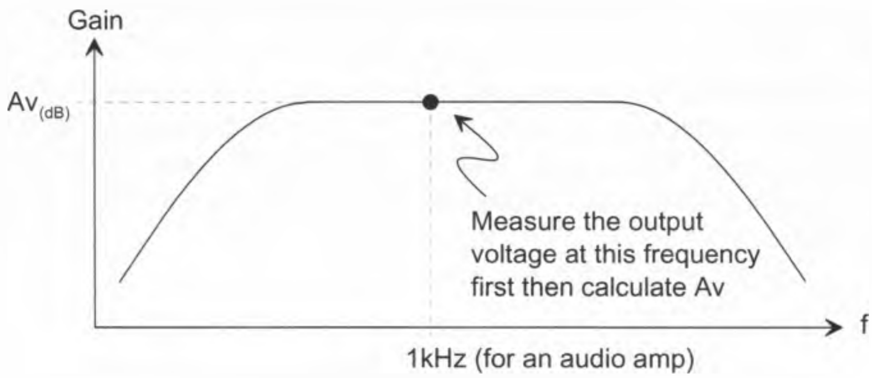


Figure 11 *The first step is to measure the gain in the midband range*

Next, reduce the frequency (not the amplitude) of your input signal until the output voltage just begins to drop. This is the beginning of the lower frequency roll-off. So, to make the next measurement in the midband region, increase the input signal's frequency a little until the voltage is the same as the maximum output voltage then record the frequency. There's no need to calculate the gain for this frequency because we already know it.

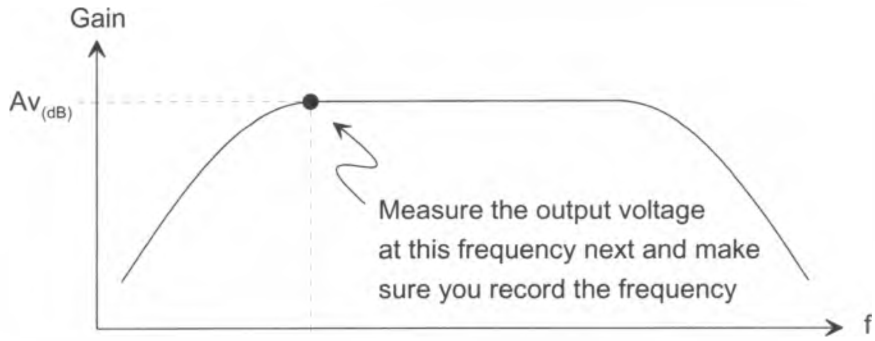


Figure 12 *Measure the gain at the low frequency end of the midband*

The next step is to measure the output voltage at three or four frequencies in the continuously changing part of the response at the lower end. The best frequency to start at is the *f1*. So, reduce the input signal's frequency until the output voltage drops to 0.707 of the maximum output voltage and record the frequency (see Figure 13). Again, there's no need to calculate the gain because we know that at *f1* it is 3dB less than the gain in the midband region.

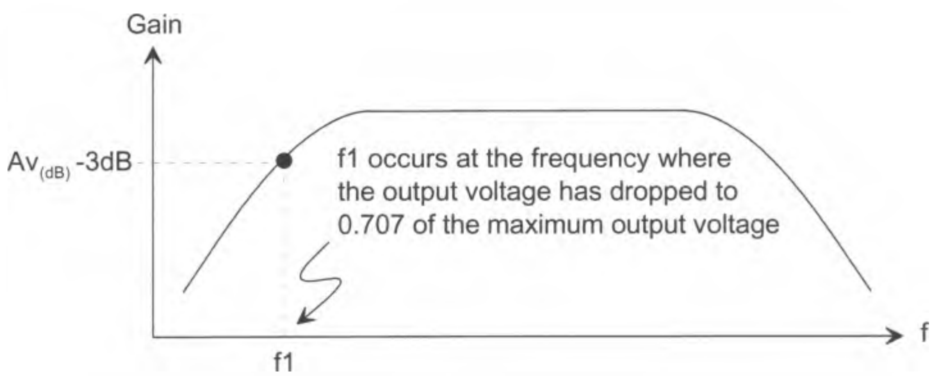


Figure 13 *Find the f1 frequency*

Then, make two or three voltage measurements at various frequencies between *f1* and the second midband output voltage you measured (see Figure 14). Don't forget to record the frequencies that you used. Next, calculate the gain at these frequencies.

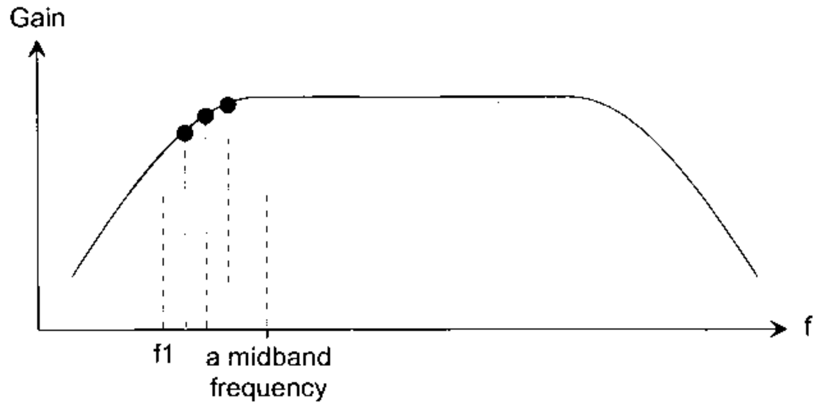


Figure 14 *Measure the gain at various frequencies in the gentle part of the roll off*

To complete the measurements on the lower part of the response, measure the output voltage and calculate the gain at two frequencies below *f1* (see Figure 15). Experience will help you decide which two frequencies but as a rough guide measure at a frequency that is half the *f1* frequency then half that again.

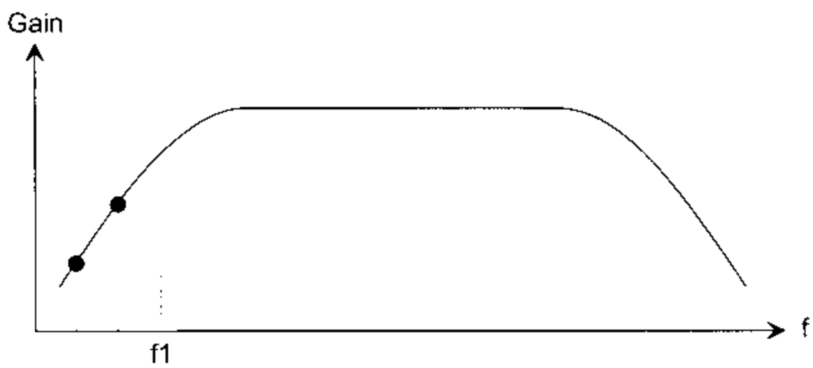


Figure 15 *Measure the gain at two frequencies below f1*

This isn't the end of your measurements and gain calculations yet. Before you can plot the frequency response you need to measure the output voltage at the same kind of points on the upper end of the response. The method is identical only you make your measurements at and around *f2*.

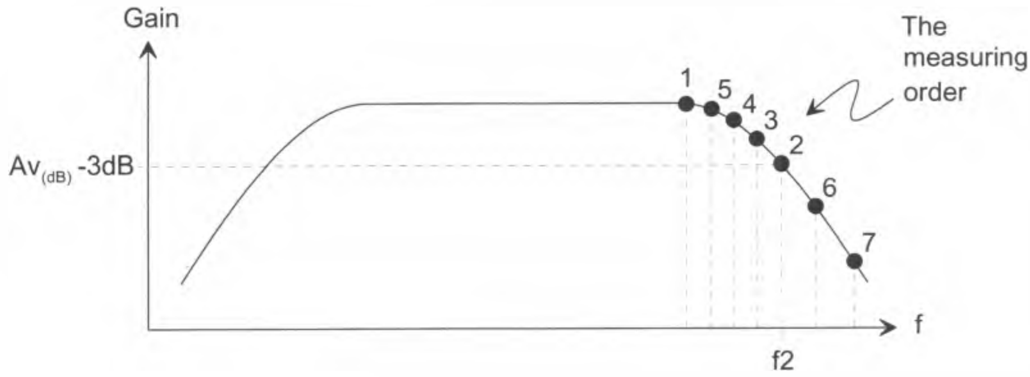


Figure 16 *The order that you could measure the gain at particular frequencies in the upper roll-off area*

Words that may be new to you

Bandwidth	The width of the band of frequencies over which the amplifier's gain is the maximum and relatively constant. It is also the area between the upper and lower roll-off frequencies.
Fall-off	The effect where the amplifier's gain starts to go down even though the input voltage hasn't changed.
Frequency response	The gain of an amplifier over a range of frequencies often shown using a graph.
Half-power points	Alternate names for *f1* and *f2*.
Lower frequency roll-off point	The frequency at the low end of the frequency response at which the amplifier's output voltage falls to 0.707 of maximum (for a constant input voltage).
Midband gain	The amplifier's gain in the flat part of the response between the *f1* and *f2* points.
Midband frequency	Any frequency that falls between *f1* and *f2*.
Roll-off	The same as fall-off.
Upper frequency roll-off point	The frequency at the high end of the frequency response at which the amplifier's gain falls to 0.707 of maximum (for a constant input voltage).
-3db points	Alternate names for *f1* and *f2*.

Skill practice 3

Practise measuring amplifier frequency response using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- Emona trainer (or a prototyping breadboard)
- 741 amplifier IC
- 1MΩ ¼W resistor
- 820kΩ ¼W resistor
- 22kΩ ¼W resistor
- 39nF capacitor
- three BNC to alligator-clip leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ____________________ ____________________ ____________________	Move bags and other objects from walkways Plan lifting of equipment Other: ____________________ ____________________ ____________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ____________________ Date: ____________________

Part A - Developing a frequency response graph

2. Gather the equipment needed for this exercise.

3. Insert the amplifier IC into the breadboard across its centre as shown in Figure 1 below.

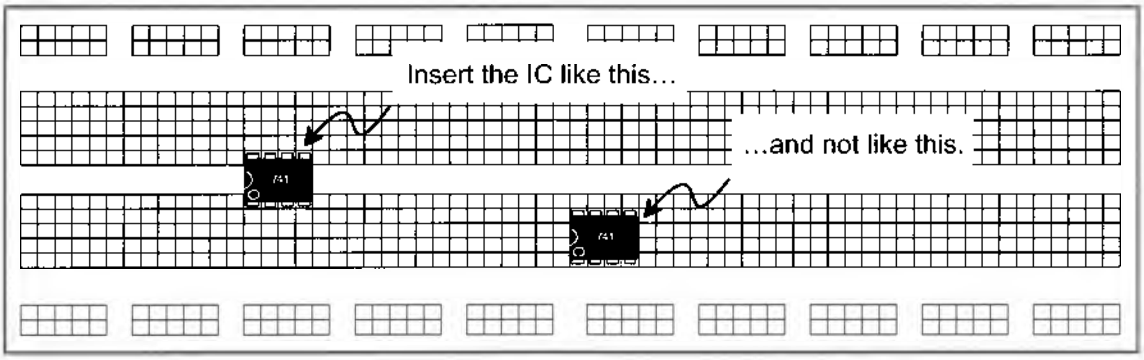


Figure 1

4. Turn off the Emona Trainer and wire the circuit in Figure 2 below.

   Note: Connect the components and wires to the IC's pins as indicated by their pin numbers.

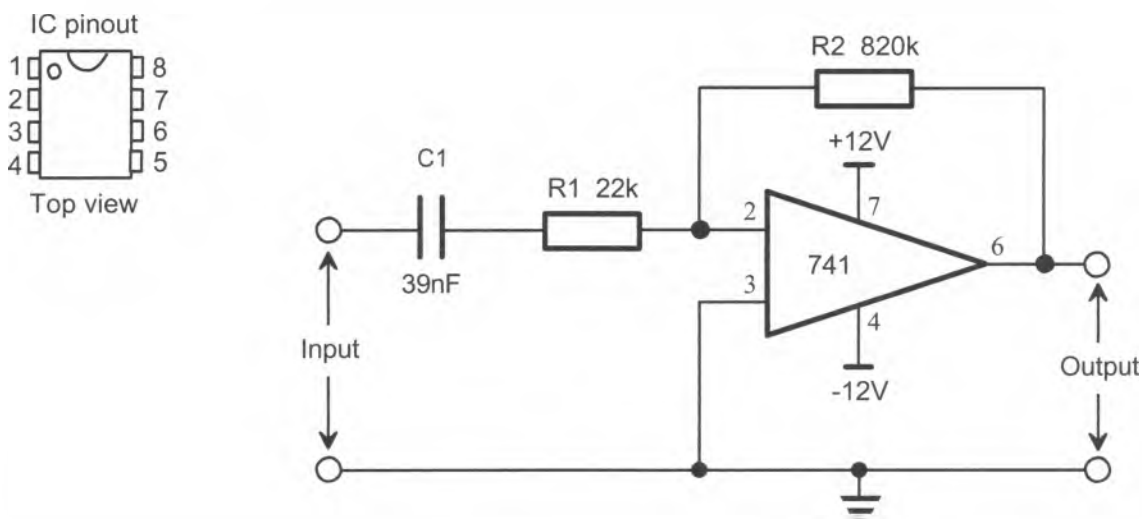


Figure 2

5. Connect the bench-mounted function generator and CRO to the circuit as shown in Figure 3 below.

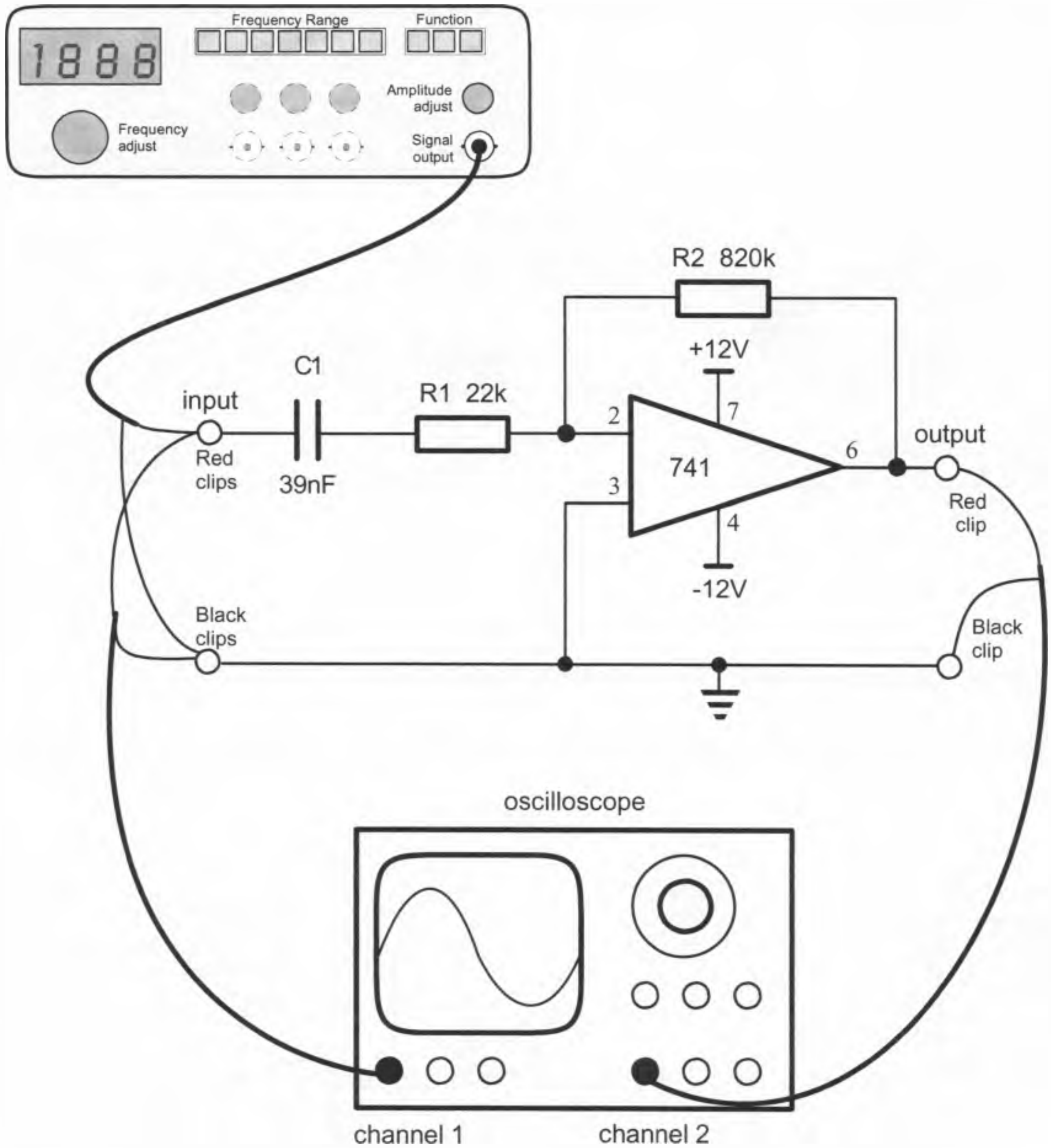


Figure 3

6. Turn on the power to the Emona Trainer and test equipment.

7. Adjust the CRO so that both channels are displayed and set the *vertical attenuation* control (the volts/div knobs) for channel 1 to *20mV/div* and for channel 2 to *0.5V/div*.

8. Set the signal generator's output for a 1kHz sinewave.

9. Adjust the signal generator's amplitude control to the middle of its travel and turn on the it's *-20dB attenuation* control.

10. You should now observe two waveforms on the CRO's display.

    Note: If you don't have two waveforms displayed on the CRO then check that it is triggered correctly. If you still don't get two waveforms, call the teacher.

11. Adjust the signal generator for a 100mV peak-to-peak signal.

    Note: If the function generator's output can't go as low as 100mV just set it to the minimum output voltage (it should be pretty close to 100mV though) and record its size.

12. Make sure that the amplifier's output voltage is not clipped. If it is, reduce the input voltage until the output is no-longer clipped and record its size.

13. Measure the amplifier's output voltage and record this information in the appropriate cell on the 1kHz row in Table 1 (on the next page).

14. Calculate and record the amplifier's gain as both a ratio and in decibels.

15. Whatever you do now, **don't** adjust the signal generator's amplitude control. If you do you'll change the input voltage and will need to start this exercise again because your results will be invalid.

16. Reduce the frequency to 800Hz. Measure and record the amplifier's output voltage and calculate the voltage gain again.

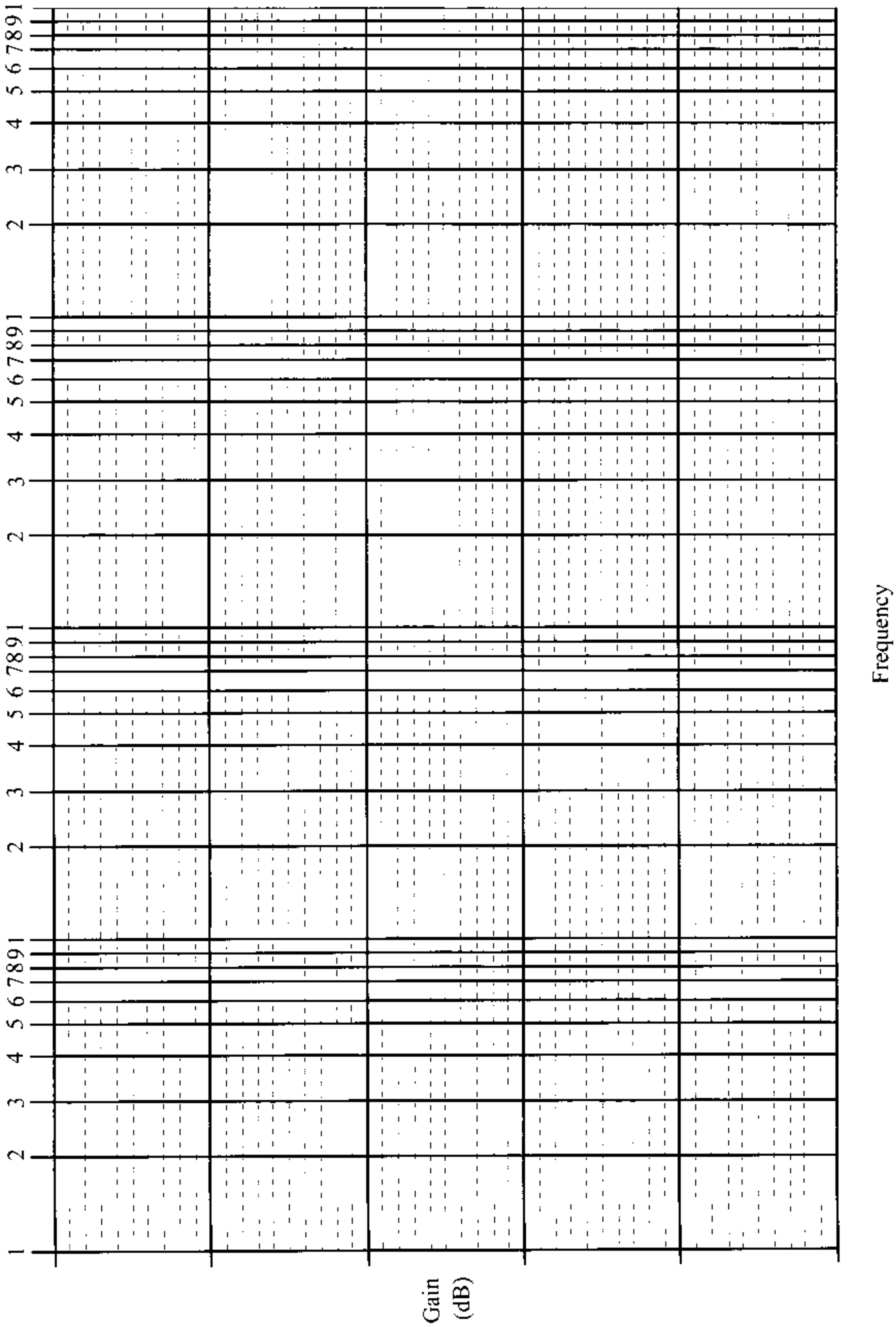
17. Repeat Step 16 for all of the frequencies listed on Table 1.

Table 1

Frequency	Output Voltage	Gain (ratio)	Gain (decibels)
20Hz			
50Hz			
100Hz			
150Hz			
200Hz			
300Hz			
800Hz			
1kHz			
5kHz			
10kHz			
15kHz			
25kHz			
50kHz			
100kHz			

The teacher needs to
check your work at
this point...

18. Using the log/lin graph paper below, plot the graph of frequency versus voltage gain (in decibels).



The teacher needs to check your work at this point...

Question 1
What is the amplifier's voltage gain (in decibels) at midband frequencies?

Question 2
That being the case, what is the amplifier's voltage gain (in decibels) at $f1$ and $f2$?

Question 3
Use this information to identify the $f1$ and $f2$ frequencies on your graph.

Question 4
Indicate the amplifier's bandwidth on your graph.

Question 5
Calculate the amplifier's bandwidth using the equation: $BW = f2 - f1$.

The teacher needs to check your work at this point...

Part B - Finding *f1* and *f2* by measurement
In Part A of this exercise you developed a frequency response graph and used it to find the amplifier's *f1* and *f2*. The second part of this exercise teaches you how to do this by measurement.

19. Set the amplifier's input signal to a midband frequency.

20. Adjust the amplifier's input signal amplitude until the amp's **output** is 7 divisions peak-to-peak **without** clipping.

21. Calculate 0.707 of 7 and record this in the space provided below:

$0.707 \times 7 =$ ______________________

22. Reduce the amplifier's input signal **frequency** until the amp's **output** is the number of divisions that you calculated for Step 21.

23. Record the frequency at which this occurs in the *f1* column of Table 2 below.

24. Return the amplifier's input signal to a midband frequency.

25. Increase the amplifier's input signal frequency until the amp's output is the number of divisions that you calculated for Step 21.

26. Record the frequency at which this occurs in the *f1* column.

Table 2

f1	*f2*

Question 6
How do your measured values of *f1* and *f2* compare with your graphed values. What might explain any differences between them?

____

____

____

Question 7

It wasn't essential to set the amplifier's output to 7 divisions to perform this test. So, what do you think is the advantage of doing so? **Tip:** If you're not sure, try calculating 0.707 of numbers other than 7.

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. What is meant by the term *bandwidth*?

2. What is a term used for any frequency that is inside the bandwidth of an amplifier?

3. What are some other terms used for *f1* and *f2*?

4. Why is log/linear graph paper used for plotting frequency response?

5. Why do *f1* and *f2* occur at the frequency where the output voltage falls to 0.707 of the maximum output voltage?

6. Why are *f1* and *f2* also known as the lower and upper -3dB points?

____

____

____

7. Draw the frequency response of an amplifier with an *f1* of 30Hz, an *f2* of 15kHz and a midband voltage gain of 700. Show the gain at the roll-off points.

8. Draw the frequency response of an amplifier with an *f1* of 500Hz, an *f2* of 2kHz and a midband gain of 72dB. Show the gain at the roll-off points.

Section 4 Loading

Purpose To develop your ability to recognise and predict the effects of loading on amplifiers.

Objectives Once you have completed this section you should be able to:

- Draw the equivalent model of a voltage amplifier and explain each part
- Explain the combined effect that an amplifier's output resistance and the load resistance have on the output voltage and voltage gain of an amplifier
- Calculate the loaded output voltage and loaded voltage gain of an amplifier
- Explain the combined effect of an amplifier's input resistance and the signal source's output resistance on the input voltage to an amplifier
- Calculate the loaded input voltage of an amplifier
- State the ideal input and output resistances for a voltage amplifier
- Use an oscilloscope to measure the unloaded and loaded voltage gain of a amplifier circuits

Introduction

This section continues to explore the concept of amplifier gain in more detail. Amplifiers are never used without having have something connected to both the input and output. They are always part of a system. Unfortunately, the load can change the amplifier's gain performance. At the same time, the amplifier can change the voltage of the signal source connected to it. Service technicians need to know how and why this happens so they don't think there is something wrong when the system is behaving as it theoretically should. To do so, we need to consider the amplifier in a new way.

The equivalent amplifier model

Regardless of what kind of amplifier we are dealing with, and from what and how it is made, it is possible to think of all amplifiers as a model having just three attributes:

- **Input resistance (*Rin*)** This is the equivalent resistance that appears across the input terminals as "seen" by the signal source. The value of this resistance depends on the electronic components inside the amplifier.
- **Internal signal generator** From a "back-box" perspective, the output voltage of an amplifier can be thought of as being produced by a signal source inside the amplifier (which is obviously not the case - it's just a model). The voltage out of this signal source can be calculated using $Av \times Vin$. This voltage is called the *unloaded output voltage* or $Vout_{(unloaded)}$.
- **Output resistance (*Rout*)** This is the equivalent resistance that appears across the output terminals as "seen" by the load looking back into the amplifier. The internal signal generator is "ideal" and so has zero resistance.

This way of simplifying an amplifier is called the *equivalent amplifier model* and is shown in Figure 1.

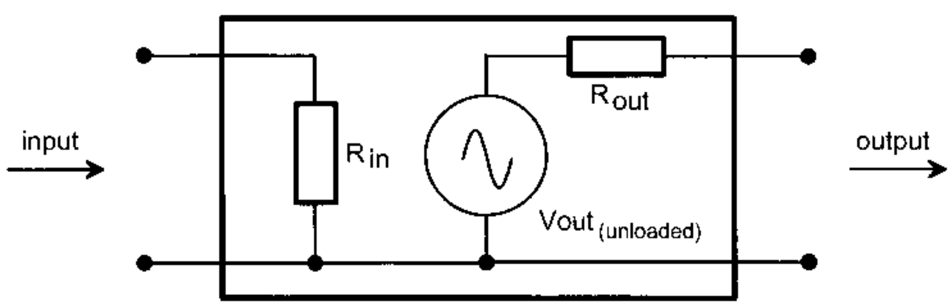


Figure 1 *Equivalent model of an amplifier showing input and output terminals*

Loaded output voltage

This equivalent amplifier model may seem a little overly theoretical but it helps us to understand a common problem with amplifiers. Not all of the amplifier's output voltage necessarily gets dropped across the load. In other words, if the output voltage of an amplifier is 20Vp-p, then when the load is connected to it the output voltage might drop significantly.

To understand why this happens consider the diagram in Figure 2 which shows a loud speaker connected to the output of an amplifier. As you can see, the amplifier's output resistance and the load form a voltage divider circuit. Recall that Kirchhoff's Voltage Law explains that, in voltage divider circuits, the applied voltage is shared among (or dropped across) the resistors. This means the voltage across each resistor is lower than the applied voltage. So, the amplifier's output voltage when a load is connected (called the *loaded output voltage*) must be lower than its unloaded output voltage.

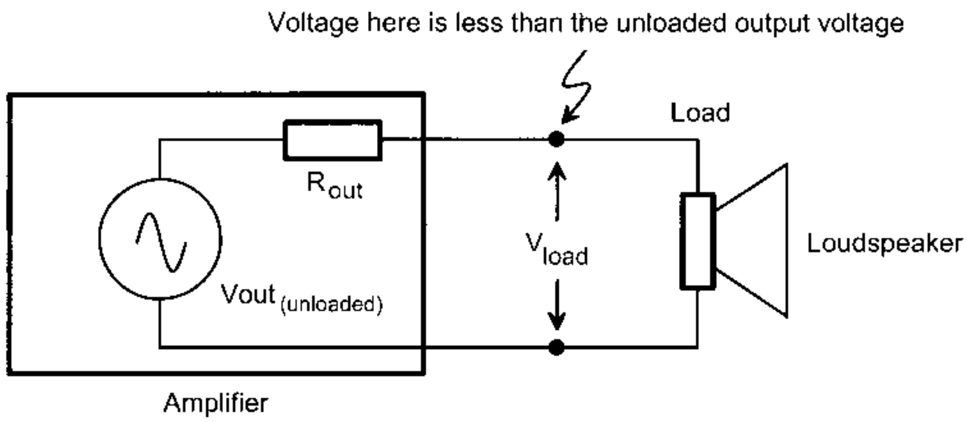


Figure 2 *The output resistance (Rout) and load resistance (R_{load}) form a voltage divider*

Let's look at an example with values. Figure 3 shows an amplifier with a gain of 50. The input signal is 40mV so the unloaded output voltage is 2V (that is, $50 \times 40mV = 2V$).

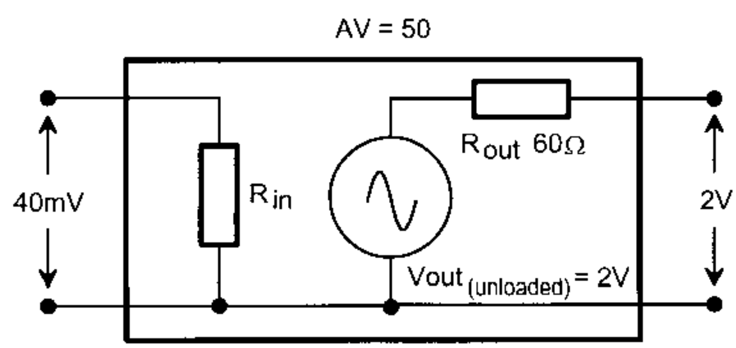


Figure 3 *The unloaded output voltage of this amplifier is 2V*

However, when a 30Ω load is connected (as shown in Figure 4) a voltage divider is formed involving the load resistor (30Ω) and the amplifier's output resistance (60Ω). This means that the amplifier's unloaded output voltage (the 2V that is said to come from a signal source inside the amplifier) is shared by the two resistors and so the loaded output voltage from the amplifier is smaller than 2V.

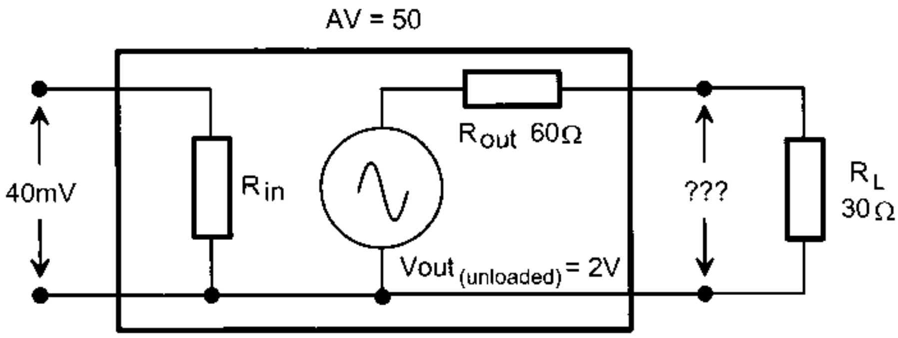


Figure 4 *The output voltage drops to 0.7V volts when a 30Ω load is connected*

The loaded output voltage is the same as the voltage across the load resistor and this can be calculated in one of two ways: a) using Ohm's Law; or b) using the voltage divider equation. Both are used below.

a) $R_T = Rout + R_L$

$R_T = 60\Omega + 30\Omega$

$R_T = 90\Omega$

$I = \frac{Vout_{(unloaded)}}{R_T}$

$I = \frac{2V}{90\Omega}$

$I = 22.22mA$

$V_{RL} = I \times R_L$

$V_{RL} = 22.22mA \times 30\Omega$

$V_{RL} = 0.667V$

b) $V_{RL} = Vout_{(unloaded)} \times \frac{R_L}{R_L + Rout}$

$V_{RL} = 2V \times \frac{30\Omega}{30\Omega + 60\Omega}$

$V_{RL} = 0.667V$

Loaded gain

As the loaded output voltage of an amplifier is smaller than the unloaded output voltage, this means that the loaded gain must be smaller also. To calculate the amplifier's loaded gain, we adapt the general gain equation ($Av = \frac{Vout}{Vin}$) to give:

$$\boxed{Av_{(loaded)} = \frac{Vout_{(loaded)}}{Vin}}$$

In the example discussed so far, the input voltage is 40mV and the loaded output voltage is 0.667V, so the amplifier's loaded gain is:

$$Av_{(loaded)} = \frac{Vout_{(loaded)}}{Vin}$$

$$Av_{(loaded)} = \frac{0.667V}{40mV}$$

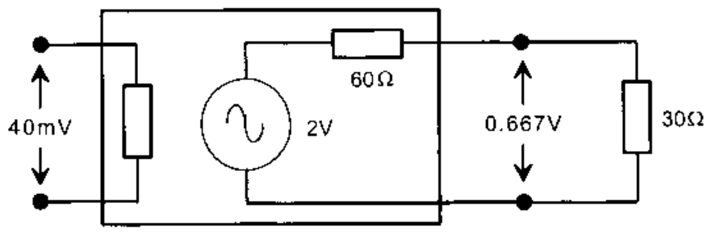
$$Av_{(loaded)} = 16.7$$

Notice that this is a good deal lower than the amplifier's quoted unloaded voltage gain of 50!

Maximising loaded output voltage/gain

Naturally, good voltage amplifier design attempts to make the loaded output voltage and the loaded gain as close as possible to the unloaded values.

To understand how this can be done, consider the amplifiers in Figures 5a and 5b. Both have an input voltage of 40mV and both have an unloaded gain of 50. This means that both would have an unloaded output voltage of 2V. However, although they both have a load of 30Ω, the amplifier in Figure 5a has a 60Ω output resistance (like the amplifier in Figure 3) and the amplifier in Figure 5b has 6Ω output resistance. The voltages across the load of both amplifiers is calculated as shown.

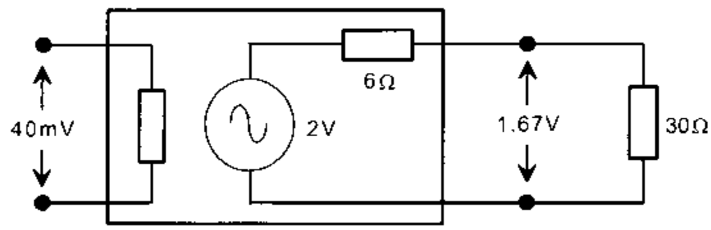


$$V_{RL} = Vout_{(unloaded)} \times \frac{R_L}{R_L + R_{out}}$$

$$V_{RL} = 2V \times \frac{30\Omega}{30\Omega + 60\Omega}$$

$$V_{RL} = 0.667V$$

(a)



$$V_{RL} = Vout_{(unloaded)} \times \frac{R_L}{R_L + R_{out}}$$

$$V_{RL} = 2V \times \frac{30\Omega}{30\Omega + 6\Omega}$$

$$V_{RL} = 1.67V$$

(b)

Figure 5 *The loaded output of an amplifier is affected by the relative resistances of the amplifier's output resistance and the load*

As you can see, the smaller the amplifier's output resistance (relative to the load resistance), the greater the loaded output voltage. It is also true to say that the greater the load resistance (relative to the amplifier's output resistance), the greater the loaded output voltage.

If we calculate the gain for the two amplifiers in Figure 5 we get:

The amplifier's loaded gain in Figure 5a is:

$$Av_{(loaded)} = \frac{0.67V}{40mV}$$

$$Av_{(loaded)} = 16.75$$

The amplifier's loaded gain in Figure 5b is:

$$Av_{(loaded)} = \frac{1.67V}{40mV}$$

$$Av_{(loaded)} = 41.75$$

From these values we can see that the smaller the amplifier's output resistance (relative to the load resistance), the greater the loaded gain. Or, that the greater the load resistance (relative to the amplifier's output resistance), the greater the loaded gain.

From these comparisons, we can draw a very important conclusion. The output resistance of a voltage amplifier needs to be much smaller than the load resistance. For an ideal voltage amplifier, the output resistance is zero ohms. This would transfer all of the amplifier's output voltage to the load making the loaded gain the same as the unloaded gain.

Typical values of output resistance for practical amplifiers made from discrete components range from 10's of ohms up to a couple of kilo ohms. Amplifiers inside ICs typically have resistances below 100Ω but they can have values below 1Ω.

Loading of the signal source by the amplifier

Just as a speaker (or some other kind of load) can load down the output voltage of an amplifier, an amplifier can load down the output voltage of its signal source. To understand how, consider the amplifier and signal source in Figure 6 below.

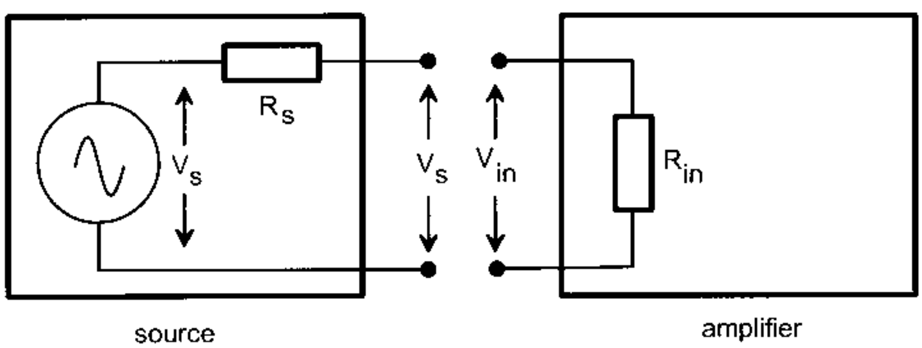


Figure 6 *A signal source and amplifier ready to be connected together*

As you can see from Figure 6, the signal source also has an output resistance. So, when the amplifier is connected to it, the amplifier's input and the source's output resistance form a voltage divider circuit reducing the signal voltage reaching the amplifier's input. See Figure 7 below.

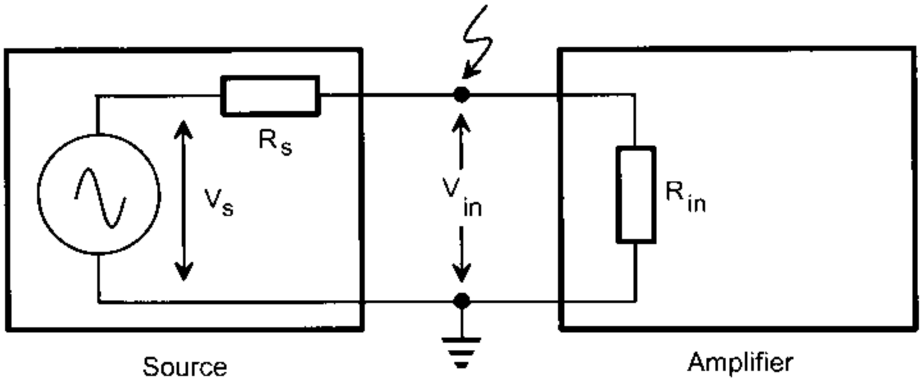


Figure 7 *The source resistance (Rs) and input resistance (Rin) form a voltage divider, reducing the amount of input signal.*

The problem with this is, your signal source might have a known output voltage of 100mV and your amplifier a known gain of 20 but connecting the two together produces an unloaded output voltage less than the 2V that it should be. Not knowing that the amplifier can load the signal source might leave you looking for a fault when in fact the situation is normal (though not necessarily desirable).

Ideally, we don't want to reduce the signal at the amplifier's input voltage. To avoid this, the input resistance of a voltage amplifier needs to be much bigger than the signal source's internal resistance. For an ideal voltage amplifier, the input resistance is infinite and this would transfer all of the source voltage to the amplifier's input.

Typical values of input resistance for practical amplifiers made from discrete components range from as little as 10's of ohms (which is not good for voltage amplifiers) up to about 50kΩ. Amplifiers inside ICs can have values from 10's of kilo ohms up to Giga ohms.

Combining the effects of loading

In practice, loading of the amplifier (which results in a lower output voltage) and loading of the signal source (which results in a lower input voltage) combine to affect the voltages around an amplifier system.

To understand this, let's do an example. The circuit of Figure 8 shows a signal source, amplifier and load ready to be connected. The signal source's unloaded output voltage is 1V and the amplifier's gain is 15. A quick calculation would suggest that the voltage across the load will be 15V. But is it?

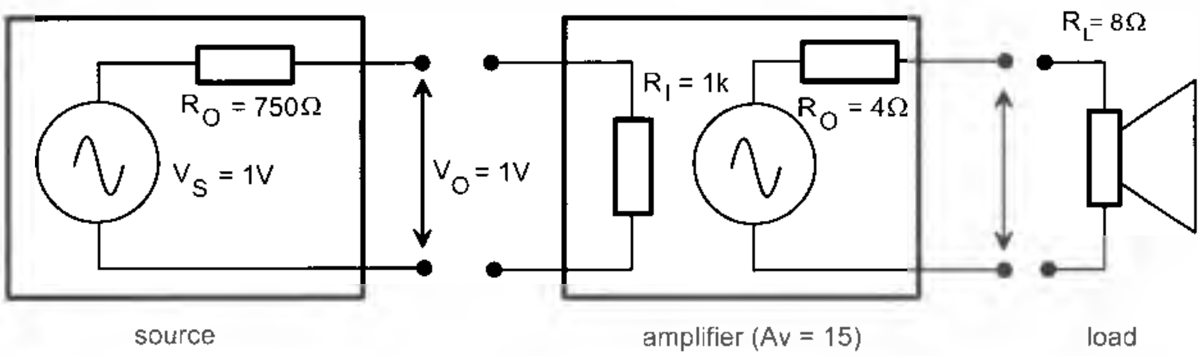


Figure 8 *Amplifier with signal source and load ready to be connected*

Connecting the signal source, amplifier and load together produces the voltages around the circuit as shown in Figure 9 below.

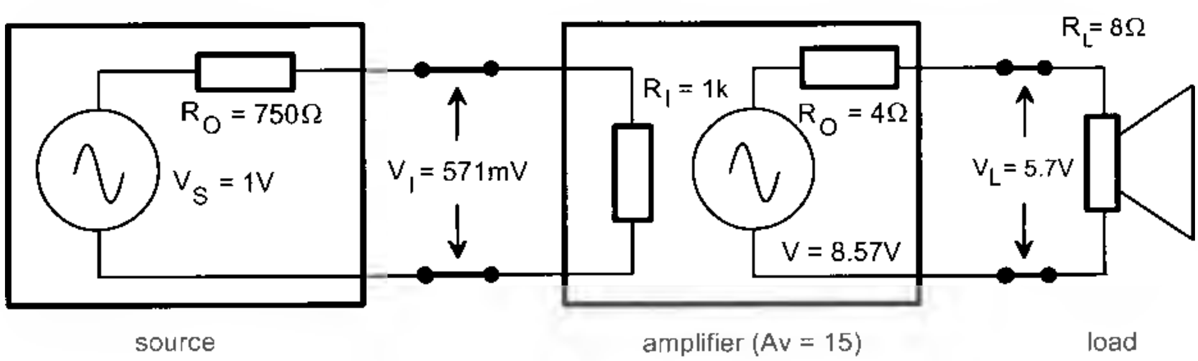


Figure 9 *Amplifier showing the voltages around the circuit when source and load are connected*

Using the information in Figure 9, we can calculate the amplifier's loaded gain. Care must be taken here though as there's a trap for new players. Your gain calculation must use the amplifier's input voltage and not the source's unloaded output as they may not be the same. That being the case:

$$Av_{(loaded)} = \frac{Vout_{(loaded)}}{Vin}$$

$$= \frac{5.7\text{V}}{0.57\text{V}}$$

$$= 10$$

Practise analysing a complete amplifier system for yourself by trying the following questions:

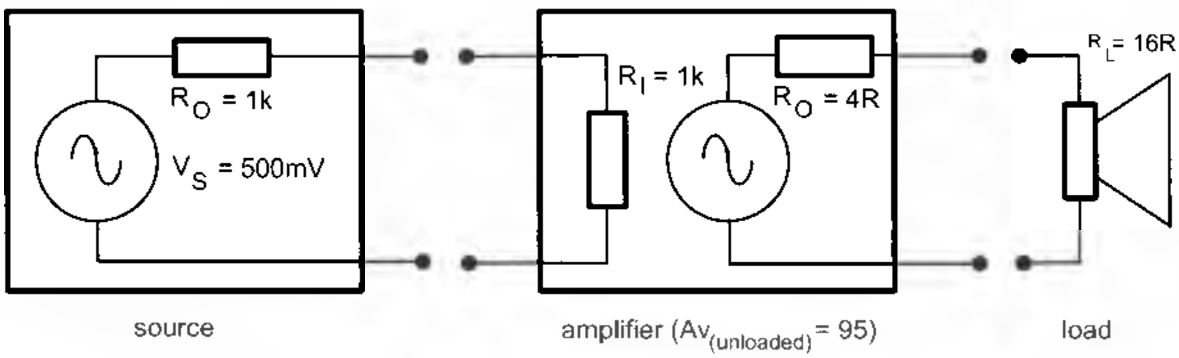


Figure 10

1. What is the voltage on the amplifier's input when the source is connected to it?

2. What is the amplifier's unloaded output voltage?

3. What is the amplifier's loaded output voltage?

4. What is the amplifier's unloaded voltage gain in decibels?

5. What is the amplifier's loaded voltage gain as a ratio **and** in decibels?

6. Calculate the amplifier's input power. **Tip:** You'll need one of the power equations for this task.

7. Calculate the power dissipated by the load.

8. Calculate the amplifier's power gain as a ratio and in decibels.

Loading in cascaded amplifiers

The circuit of Figure 11 shows us that loading problems must also affect the gain performance of cascaded amplifiers.

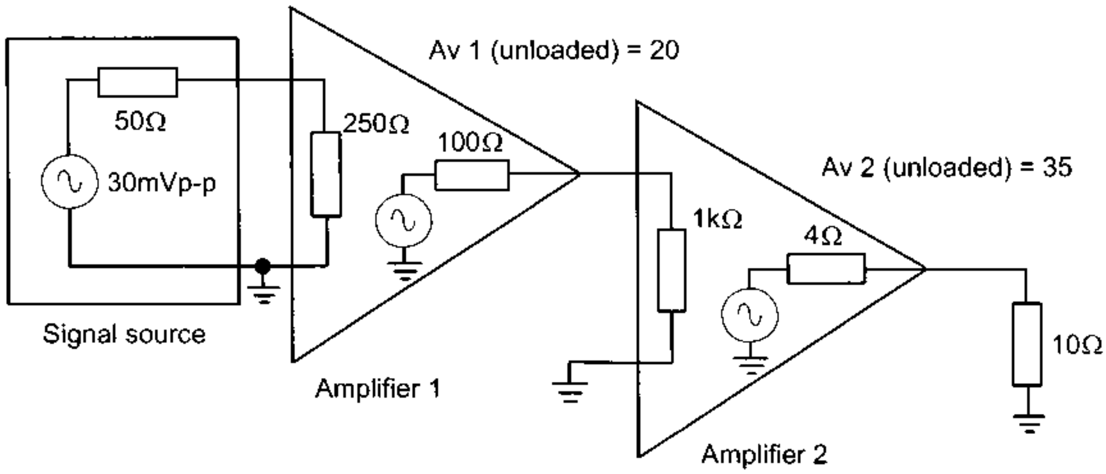


Figure 11 *Cascaded amplifier showing values for input and output resistances as well as load resistance*

At first glance, the cascaded amplifier's voltage gain is 700 (20 × 35). However, the actual gain is much lower than this due to loading. The following analysis shows how the cascaded amplifier's loaded gain is found.

The voltage that appears at the input of this amplifier is:

$$Vin_{(1)} = Vs \times \frac{Rin}{Rs+Rin}$$

$$Vin_{(1)} = 30mV \times \frac{250\Omega}{50\Omega+250\Omega}$$

$$Vin_{(1)} = 25mV$$

The unloaded output voltage of amplifier 1 is:

$$Vout_{(1)} = Vin_{(1)} \times Av$$

$$Vout_{(1)} = 25mV \times 20$$

$$Vout_{(1)} = 500mV$$

However, the input voltage to amplifier 2 is:

$$Vin_{(2)} = Vout_{(1)} \times \frac{Rin_2}{Rout_1 + Rin_2}$$

$$Vin_{(2)} = 500mV \times \frac{1k}{100\Omega + 1k}$$

$$Vin_{(2)} = 454.5mV$$

The unloaded output voltage of amplifier 2 is:

$$Vout_{(2)} = Vin_{(2)} \times Av$$

$$Vout_{(2)} = 454.5mV \times 35$$

$$Vout_{(2)} = 15.9V$$

However, the voltage across the load is:

$$V_L = Vout_{(2)} \times \frac{R_L}{Rout_2 + R_L}$$

$$V_L = 15.9V \times \frac{10\Omega}{4\Omega + 10\Omega}$$

$$V_L = 11.36V$$

So the gain of amplifier 1 when loaded by amplifier 2 is:

$$Av_{(1)} = \frac{Vin_2}{Vin_1}$$

$$Av_{(1)} = \frac{454.5mV}{25mV}$$

$$Av_{(1)} = 18.8$$

And the loaded gain of the cascaded amplifier is:

$$Av = \frac{V_L}{Vin_1}$$

$$Av = \frac{11.36V}{25mV}$$

$$Av = 454.4$$

This value of gain is much lower that the gain of 700 that was initially calculated!

Note: Although these calculations are relevant to your work as a technician, you'll not be asked a question as difficult as this in the exams for this subject.

Words that may be new to you

Amplifier equivalent model	Another way of thinking about an amplifier without getting into the detail about what is actually inside it. It consists of an input resistance, an an internal signal source and an output resistance.
Input resistance	The total effective resistance that is "seen" when looking into the input of a circuit.
Internal signal generator	A simplified way of thinking about where the output voltage of an amplifier comes from.
Loaded gain	The gain of an amplifier when a load is connected to its output.
Loaded output voltage	The voltage measured at the output of an amplifier with a load connected to it. The loaded output voltage is the same as the voltage across the load.
Output resistance	The resistance inside the amplifier that appears in series with its output.
Unloaded gain	The gain of an amplifier without a load connected to its output.
Unloaded output voltage	The voltage measured at the output of an amplifier without a load connected to it.

Student notes

Skill practice 4

Practise measuring the unloaded and loaded voltage gain of amplifier circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Emona trainer (or a prototyping breadboard)
- decade box
- 741 amplifier IC
- 270Ω ¼W resistor
- 820Ω ¼W resistor
- 5k6Ω ¼W resistor
- 0.22μF capacitor
- three BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
    - use and maintain machinery, tools and all other equipment properly and safely
    - ensure that your work area is free of hazards
    - notify a TAFE NSW staff member of actual or potential hazards
    - wear/use prescribed safety equipment
    - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ________________ ________________ ________________	Move bags and other objects from walkways Plan lifting of equipment Other: ________________ ________________ ________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ________________ Date: ____________

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1.

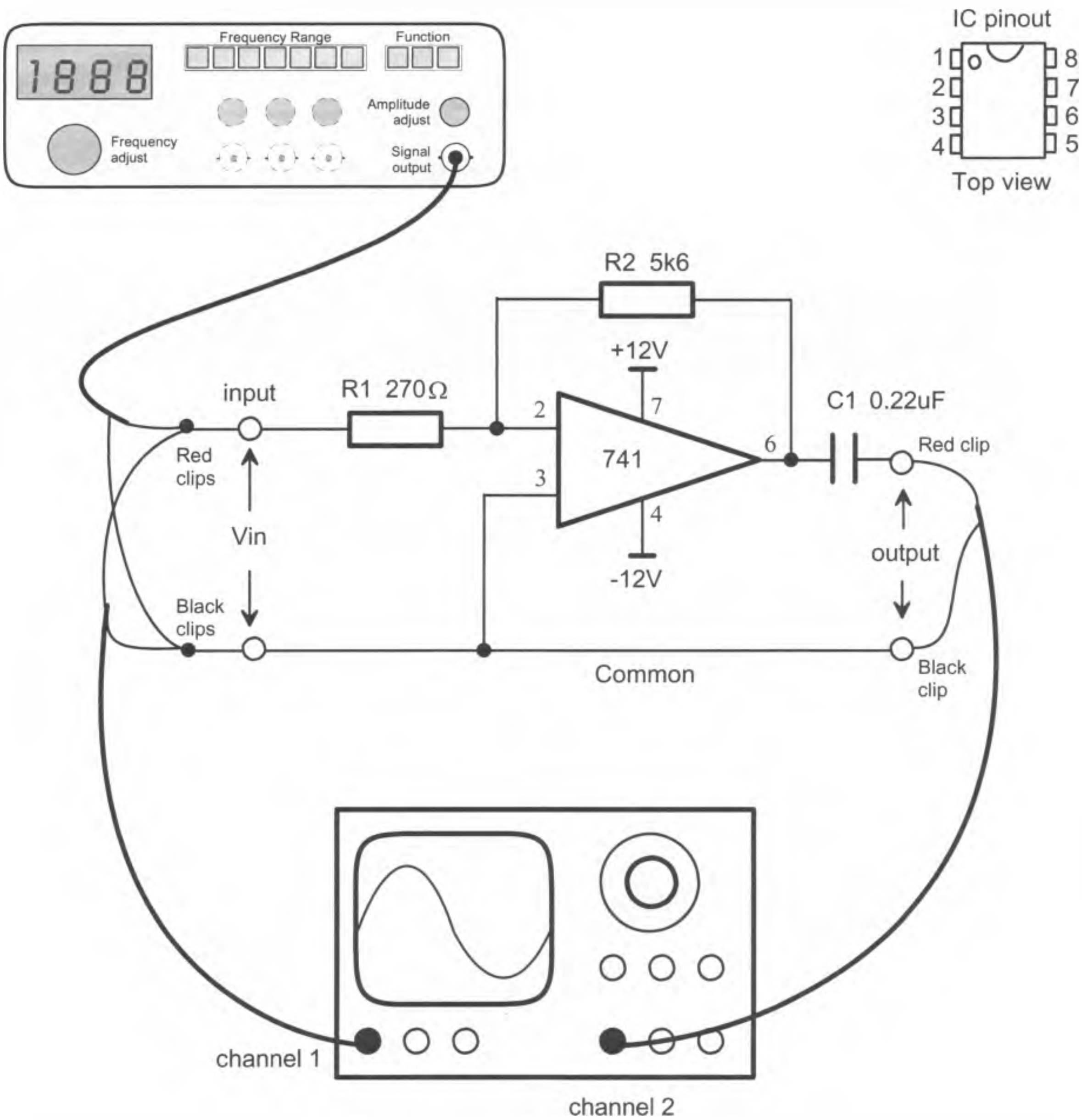


Figure 1

Questions 7 to 9 refer to the circuit in Figure 3 below

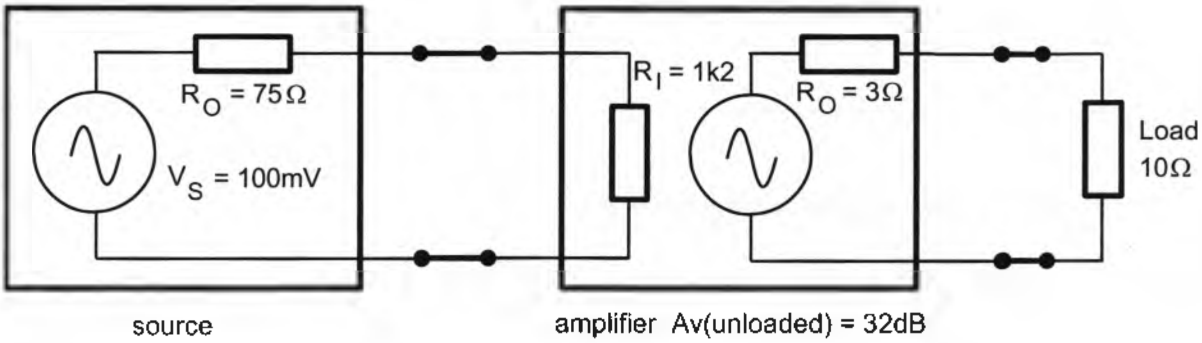


Figure 3

7. (a) What is the amplifier's input voltage?

(b) What is the amplifier's unloaded output voltage?

(c) What is the amplifier's loaded output voltage?

(d) What is the amplifier's loaded voltage gain in decibels?

8. (a) What is the amplifier's input power?

(b) What is the amplifier's output power?

(c) What is the amplifier's power gain in decibels?

9. What would you expect to happen to the amplifier's loaded gain if the load resistor's value went up?

Questions 10 and 11 refer to the circuit in Figure 4 below

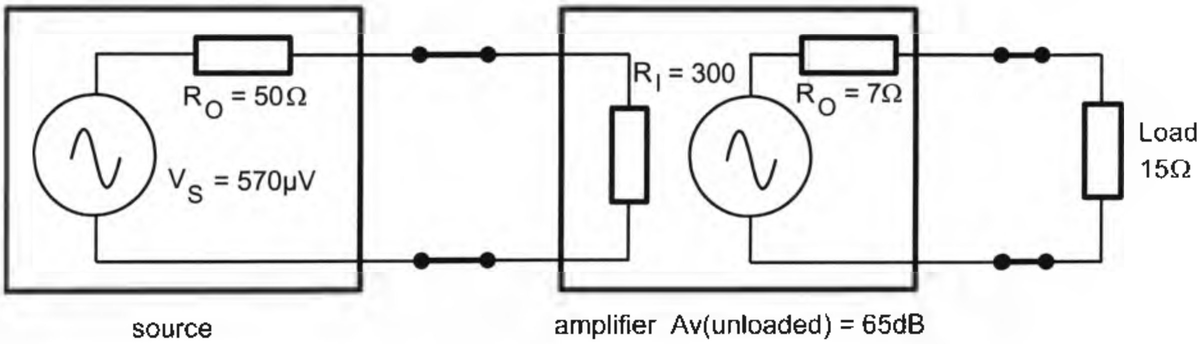


Figure 4

10. What is the amplifier's loaded voltage gain in decibels?

11. What is the amplifier's power gain in decibels?

Student notes

Section 5 Operational amplifiers; and The comparator

Purpose To develop your ability to predict the output voltage of operational amplifiers operated in open-loop mode.

Objectives Once you have completed this section you should be able to:

- List the characteristics of an ideal amplifier including voltage gain, input resistance, output resistance, distortion and bandwidth
- Give typical figures for the following op amp characteristics (open-loop mode): voltage gain, input resistance, output resistance and bandwidth
- Define the terms *open-loop mode* and *open-loop voltage gain*
- Explain the operation of an op amp operated in the open-loop mode
- Predict the output voltage of an op amp operated in the open-loop mode for given values of supply voltages and input voltages
- Explain the operation of an op amp operated in open-loop mode to implement a comparator
- Predict the output voltage of a comparator given values for the supply voltages and input voltages
- Give applications for comparators
- Verify the operation of the operational amplifier in open-loop mode

Introduction

In this section we'll consider common amplifier characteristics that the service technician should know about and look at practical and ideal values for these. Then we'll look at the *operational amplifier* (also known as the op amp) and see how it approaches the ideal amplifier in many ways. Next, we'll consider the limitations of op amps which will lead to a discussion of a classic open-loop op amp circuit called the *comparator*.

Amplifier characteristics

When thinking about going on holiday you probably have in mind certain characteristics that would be essential. Such characteristics might include things like: destination, how much you're prepared to pay, temperature, what you want to see and do when you get there, and so on. You can use this information to compare the types holidays that you could possibly go on and choose the one that you most appropriate at the time.

In the same way, amplifiers have characteristics that can be used to compare them with each other and you have already learnt about five of the most important of them. They are gain, bandwidth, input resistance, output resistance and distortion.

Characteristics of ideal amplifiers

If time or money was not an issue, there is probably a holiday that you would like to take that is your idea of the perfect or "ideal" holiday. In a similar way, there is also the notion of the ideal amplifier.

The characteristics of an ideal voltage amplifier include:

- infinite gain
- infinite bandwidth
- infinite input resistance
- zero output resistance
- zero distortion

The ideal amplifier doesn't really exist but there are devices called operational amplifiers (or op amps) with characteristics that can be enhanced and approach the ideal.

What are operational amplifiers?

Op amps are cascaded amplifiers made from transistors, resistors and capacitors all squeezed into an integrated circuit (IC).

Schematic symbol

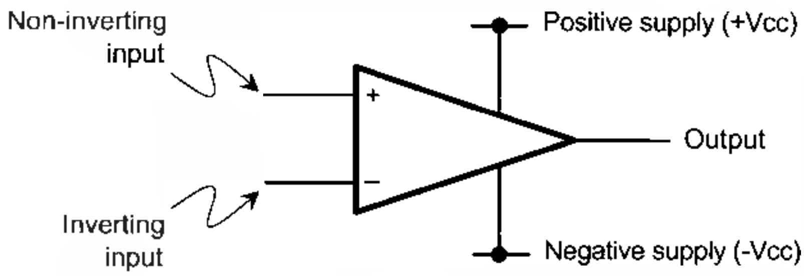


Figure 1 *Schematic symbol for an op amp with a dual rail supply*

At a minimum, op amps have five pins. One is the output, two are inputs called the "non-inverting input" and the "inverting input" and two pins are for the power supply connections (though, these two pins are sometimes not shown). The majority of op amps are dual rail devices and so require both a positive supply voltage and a negative supply voltage to operate correctly. The two voltages should be the same magnitude and op amps typically work off supply voltages from ±3V to ±18V which makes them well suited to battery-operated equipment.

Op amp characteristics

Op amps are popular devices because the values for gain, input resistance, output resistance and distortion are excellent. Op amps typically have input impedances measured in Mega ohms, output impedances under 100Ω, gains running into the millions and distortion figures so low it is not worth worrying about (from a hearing perspective).

The only amplifier characteristic of the op amp that is poor is the bandwidth which is typically as low as 10Hz. However, as you will see in the next chapter, the bandwidth of op amps can be improved dramatically by sacrificing some of the gain. And in the process, the op amp's input resistance, output resistance and distortion get even better and effectively approach the values of the ideal amplifier.

Op amp operation n open-loop mode (ie without negative feedback)

The way in which an op amp works is very simple. It amplifies the difference between the non-inverting input and the inverting input. When the op amp is operated in open-loop mode (that is, without any components connected from the output to the inverting input), the theoretical output voltage can be predicted using the equation:

$$Vout = (Vin_{non-inverting} - Vin_{inverting}) \times Av_{OL}$$

In this equation...

- $Vout$ is the op amp's output voltage
- $Vin_{non\text{-}inverting}$ is the voltage on the op amp's non-inverting pin (the one marked "+") with respect to the circuit's common
- $Vin_{inverting}$ is the voltage on the op amp's inverting pin (the one marked "-") with respect to the circuit's common
- Av_{OL} is the op amp's gain (called the "open-loop gain") and is specified by the manufacturer.

Let's put this equation into practice. Figure 2 shows an op amp with 15µV on the inverting input and 25µV on the non-inverting input. What is the theoretical output voltage?

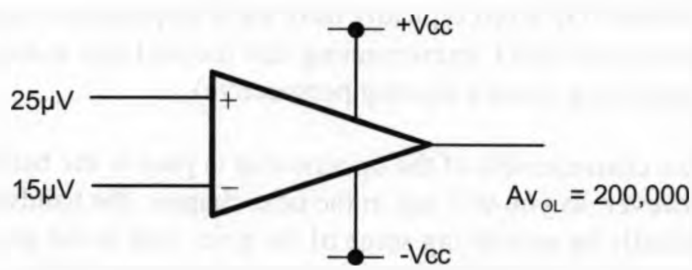


Figure 2 *Op amp with a difference of +10µV between the inputs*

$$Vout = (25\mu V - 15\mu V) \times 200,000$$

$$Vout = 2V$$

Practise using this equation for yourself by trying the following questions.

1. What is the theoretical output voltage of an op amp with an open-loop gain of 400,000, 15µV on the inverting input and -2.5µV on the non-inverting input?

2. What is the theoretical output voltage of an op amp with an open-loop gain of 2,000,000, 18µV on the inverting input and 7µV on the non-inverting input?

Limitations of op amps operated in the open-loop mode

As you know, the output voltage of any amplifier cannot exceed its power supply (first mentioned in Section 1). This is true of op amps too.

Knowing this, consider Figure 3 below which shows an op amp operated in open-loop mode with ±12 supply rails. It's inverting input is connected to common (represented by the earth symbol) and so is zero volts. The non-inverting input is connected to a variable DC voltage source.

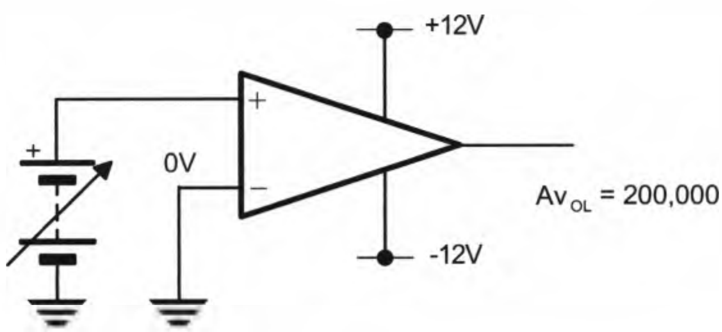


Figure 3

According to the equation that predicts an op amp's output voltage (see Page 5-4), the output voltage of this op amp will be 200,000 times whatever the voltage is on the op amp's non-inverting input because the inverting input is 0V.

Table 1 below shows what happens to the op amp's output voltage as the variable DC input voltage increases in 10μV increments from 0V.

Table 1

$Vin_{non\text{-}inverting}$	Theoretical output voltage	Actual output voltage
0V	0V	0V
10μV	2V	2V
20μV	4V	4V
30μV	6V	6V
40μV	8V	8V
50μV	10V	10V
60μV	12V	12V
70μV	14V	12V
80μV	16V	12V
90μV	18V	12V
100μV	20V	12V

Notice that, as the input voltage gets bigger, the output voltage gets proportionally bigger also. But notice also that the relationship breaks down once the output voltage reaches 12V. As the input voltage continues to rise, the output should theoretically be getting bigger too but that doesn't happen because the positive supply rail (+*Vcc*) is +12V and the output voltage can't be bigger than that. So, once difference between the op amp's inputs exceeds 60μV (in this example but it's a typical figure), the op amp is being overdriven.

Now, if we know an op amp's gain and power supply voltages, we can work backwards to find the maximum allowable difference in voltage between any open-loop op amp's inputs using the equation:

$$Vin_{(\max)} = \frac{Vout_{(\max)}}{Av_{OL}}$$

Using it for the circuit in Figure 3, we get...

$$Vin_{(\max)} = \frac{Vout_{(\max)}}{Av}$$

$$Vin_{(\max)} = \frac{\pm 12V}{200{,}000}$$

$$Vin_{(\max)} = \pm 60\mu V$$

So, for example, if one of this op amp's inputs is 1V, then the other input cannot be a voltage bigger than 1.00006V (ie 1V + 60μV) or smaller than 0.99994V (ie 1V - 60μV).

Why does any of this matter? Because this maximum allowable difference been input voltages is almost impossible not to exceed. That's because it's impossible to design circuits for the "front end" of op amps (ie at the inputs) that are exactly 0V in the first instance. One input might have 0.0001V on it and the other might have 0.00003V on it, which are both crazy-small voltages, but the difference between them is 70μV and so the op amp would be overdriven.

Moreover, you can't use an external voltage source (like in Figure 3) to correct the difference and make the two voltages exactly the same because of the difficulty - and hence expense - of doing so.

Does this mean that op amp's are useless?

No. Of course not, or they would not have been invented and they would not be such widely used ICs. The problem is solved by introducing an effect called *negative feedback* which operates op amps in a closed-loop mode and turns them into excellent small signal amplifiers. Negative feedback is explained in the next chapter and the remainder of the workbook teaches you about some widely used closed-loop op amp circuits.

With that said, op amps operated in open-loop mode are excellent for implementing a circuit called the *comparator*.

The comparator

Figure 4 below shows the circuit of a comparator. As you can see, it's just an op amp operated in open-loop mode.

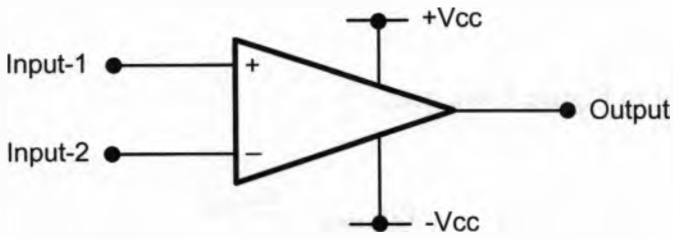


Figure 4 *An op amp operated in the open-loop mode makes an excellent comparator*

Operation

To understand the comparator's operation lets compare the theoretical output voltages for an op amp with an Av_{OL} of 200,000 if *Input-1* was 5V and *Input-2* was any voltage is less positive, let's say 4.9V for example, with what would happen if the input voltages are reversed. The calculations are shown below.

$$Vout = (Vin_{non\text{-}inv} - Vin_{inv}) \times Av_{OL} \qquad Vout = (Vin_{non\text{-}inv} - Vin_{inv}) \times Av_{OL}$$

$$Vout = (5V - 4.9V) \times 200{,}000 \qquad Vout = (4.9V - 5V) \times 200{,}000$$

$$Vout = +20{,}000V \qquad Vout = -20{,}000V$$

Of course, the actual output voltage isn't going to be plus or minus 20,000V! The most it can be is whatever the positive supply rail is (*+Vcc*) or whatever the negative supply rail is (*-Vcc*). But, it's not the size of the output voltage that matters with comparators. Instead its the polarity of the output voltage and we see an interesting thing if we summarise the information above using Table 1 below.

Table 1

Input-1	Input-2	Which input is more positive?	Output voltage
5V	4.9V	$Vin_{non\text{-}inverting}$ is more positive than $Vin_{inverting}$	+Vcc
4.9V	5V	$Vin_{non\text{-}inverting}$ is less positive than $Vin_{inverting}$	-Vcc

Notice that when the voltage on *Input-1* is positive relative to a voltage than *Input-2*, the output voltage is positive. But when the voltage on *Input-1* is negative relative to the voltage on *Input-2*, the output voltage is negative.

Applications

The comparator finds use in many places where electronic equipment needs to "know" the condition of an electrical or physical property and the condition is a choice of only two options. For example, is the door open or closed, is it light or dark, is the oven too hot or not hot enough, is the fridge too cool or not cool enough, is there a car in the right turn lane or not, and so on.

Comparators are found in equipment such as electronics control systems (for example, temperature control in ovens and refrigerators), alarms systems, light sensing circuits, air-conditioning systems, robotics, traffic light controllers and so on. In these examples, the comparator is designed to work with transducers of some sort to detect the condition being monitored. Commonly used transducers include: thermocouples, thermistors, light dependant resistors (LDRs), reed switches and so on.

For a simple example of how a comparator can be used, consider the circuit in Figure 5 below. The comparator's *Input-1* is connected to the junction of a voltage divider set-up using *R1* and an LDR and its *Input-2* is connected to a fixed 5V and is called the *reference* voltage. (How that fixed 5V is set-up is irrelevant to this explanation but it can be done in a number of ways including using a simple voltage divider made using two resistors.)

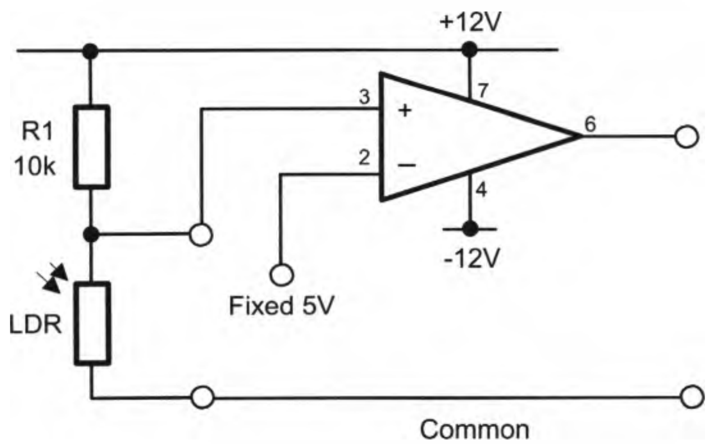


Figure 5 *A comparator used to react to changes in ambient light*

Recall that LDRs change resistance linearly from a very high resistance when it's dark to a very low resistance when it's light. So, when it's dark, the potential difference across the LDR, and hence the voltage on *Input-1*, would approach the supply voltage (so, let's say 10V). When it's light, the potential difference across the LDR, and hence the voltage on *Input-1* would approach 0V (so, let's say 2V).

Now, in the middle of the day when it's light, the 2V on the comparator's *Input -1* is more negative than the 5V on its *Input-2* and so the op amp's output would be *-Vcc*. But as the sun begins to set and the amount of daylight decreases, the LDR's resistance would gradually rise and so would the voltage across it and hence the voltage on *Input-1*. As it gets darker, the voltage on *Input-1* would gradually increase towards 10V.

At some point, the decreasing daylight would cause the LDR's resistance to be big enough so that its potential difference, and hence the voltage on *Input-1*, would be fractionally bigger than the 5V reference. When that happens, the op amp's output would flip to *+Vcc*.

If this arrangement was being used to control auto-on street lights then, when it's light, the -Vcc on the op amp's output would by used by additional circuitry (not shown here) to turn the street lights off. When it's dark enough, the +Vcc on the op amp's output would be used by the additional circuitry to turn the street lights on.

[As an aside, there is a problem with this simple circuit being used to turn street lights on and off. A passing cloud near sunset could temporarily dim the sunlight and cause the street lights to turn on then back off again a short time later once the cloud has passed. Another passing cloud would do the same so you would have a situation where the street lights would be turning on and off multiple times before they finally turn on for the night. This problem is solved by introducing an effect into the operation of the comparator called *hysteresis*. The *Schmitt Trigger* is a comparator circuit with hysteresis. According to the unit descriptor, hysteresis and the Schmitt Trigger are not meant to be taught nor assessed for this unit and this is only mentioned here for your interest. You'll learn about the Schmitt Trigger for another unit.]

Words that may be new to you

Closed-loop gain	The gain of an op amp when it has been wired in the closed-loop mode (that is, with negative feedback).
Closed-loop mode	A mode of op amp operation where the circuit has been wired so that it has negative feedback.
Dual rail supply	A power supply designed to provide two supply rails to a circuit usually with one positive and the other negative.
Inverting input	The input to an op amp marked by the minus (-) symbol.
Non-inverting input	The input to an op amp marked by the plus (+) symbol.
Op amp	Short for operational amplifier.
Open-loop gain	The gain of an op amp without negative feedback. This gain is always specified by the manufacturer.
Open-loop mode	A mode of op amp operation that does not include any negative feedback.
Operational amplifier	Usually abbreviated to "op amp", this is a device consisting of a cascaded amplifier made from many components all squeezed into one chip.
Negative feedback	A process where a sample of an amplifier's output voltage is feedback to the input. On an op amp it must be fed back to the inverting input.
Supply rail	A line in a schematic diagram, or a track on a PCB that carries the supply voltage around the circuit.

Student notes

Skill practice 5

Practise measuring the output voltage of comparators using a DMM

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 45 minutes to complete this exercise.

Equipment

- Emona Trainer
- DMM
- LM741 op amp
- 1k2Ω ¼W resistor
- 10kΩ ¼W resistors
- light-dependant resistor
- LED
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

<table>
<tr><td colspan="2">

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
    - use and maintain machinery, tools and all other equipment properly and safely
    - ensure that your work area is free of hazards
    - notify a TAFE NSW staff member of actual or potential hazards
    - wear/use prescribed safety equipment
    - take notice of any safety signs and adhere to their instructions

</td></tr>
<tr><td>

Risks involved in this activity include:

Trip hazards (eg students bags)
Objects dropped on feet (while equipment is taken to and from workbenches).

Others: ______________________

____

____

</td><td>

Control measures:

Move bags and other objects from walkways
Plan lifting of equipment

Other: ______________________

____

____

</td></tr>
<tr><td colspan="2">

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ______________________ Date: ______________________

</td></tr>
</table>

2. Gather the equipment needed for this exercise.

3. Adjust the right-side output of the bench-mounted DC power supply to zero volts.

4. Connect the circuit of Figure 1 below. Use the bench-mounted power supply for *Vin*.

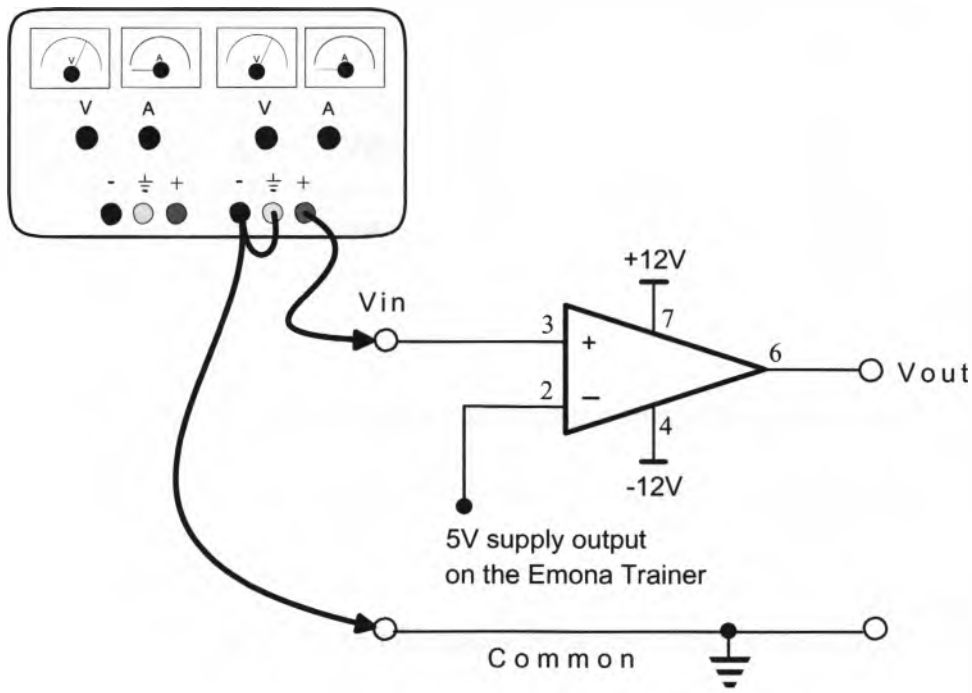


Figure 1

5. Turn on the Emona Trainer and the bench-mounted power supply.

6. Measure the op amp's output voltage. Record the value in Table 1 (on the next page).

Table 1

Vin	Vout	Vin	Vout
0V		5.5V	
1V		6V	
2V		7V	
3V		8V	
4.5V		9V	

7. Increase the bench-mounted power supply's output voltage to 1V and repeat Step 6.

8. Repeat Steps 6 and 7 for all of the remaining voltages in Table 1.

Question 1
Why was the op amp's output a negative voltage for inputs below 5V?

Question 2
Why was the op amp's output a positive voltage for inputs above 5V?

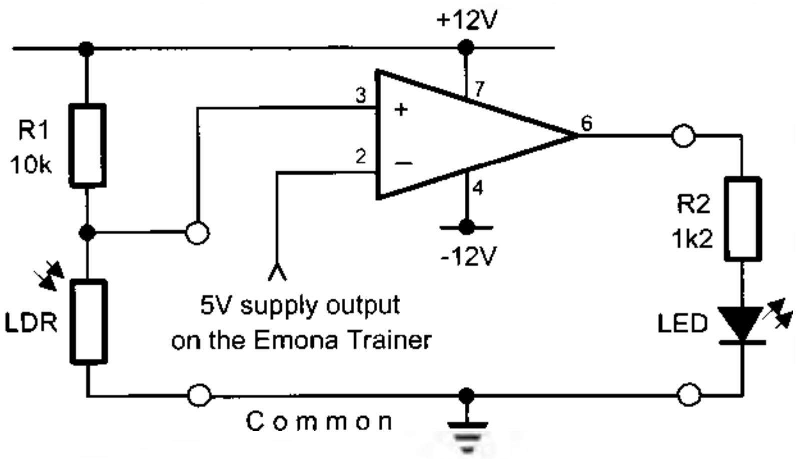
---

9. Try to set the bench-mounted power supply's output voltage so that the op amp's output is 0V.

Question 3
Why did you find it impossible to perform Step 9?

The teacher needs to check your work at this point...

10. Modify the circuit as shown in Figure 2 below.



To help you wire the LED correctly...

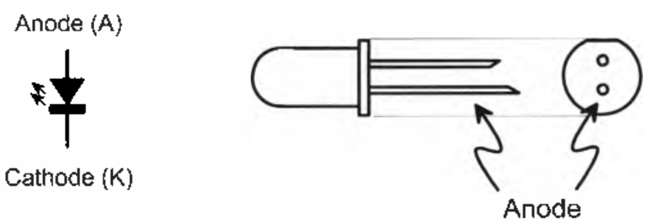


Figure 2

11. Turn on the Emona Trainer.

12. Cover then uncover the face of the light dependant resistor while watching the LED. **Note:** If nothing happens check your wiring.

13. With the LDR's face uncovered (so, exposed to light), measure the voltage on the op amp's non-inverting input pin. Record this voltage in Table 2 below.

14. Measure the voltage at the output of the op amp and record this value.

15. Cover the face of the LDR then measure and record the two voltages again.

Table 2

Light		Dark	
Vin	**Vout**	**Vin**	**Vout**

Question 4
Explain why the output voltage is negative when the LDR is exposed to light.

Question 5
Why is the LED off when the op amp's output is negative?

Question 6
Explain why covering the LDR causes the output of the op amp to become positive.

____

____

____

Question 7
Why is the LED on when the op amp's output is positive?

____

____

____

Question 8
Give an application where this circuit could be used.

____

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. List the characteristics of an ideal voltage amplifier.

2. Draw the schematic symbol for a dual rail op amp and label all inputs and the output.

3. Which characteristic of an op amp is far from the ideal? And, what is a typical value for this characteristic?

4. What is meant by the term open-loop gain?

5. What is a typical value of open-loop gain for op amps?

6. Why are op amps almost unusable as amplifiers in the open-loop mode of operation?

7. Is the closed-loop gain of an op amp lower or higher than the open-loop gain?

8. What is the main factor that affects the maximum output voltage of an op amp?

9. Why do the majority of op amps have both a positive and negative supply rail?

10. For the circuit of Figure 1, indicate on the table below whether the output voltage is +9V or -9V given the input voltages given.

    Tip: Write the name of the inputs on the drawing. Remember, "+" denotes the non-inverting input and "-" denotes in inverting input.

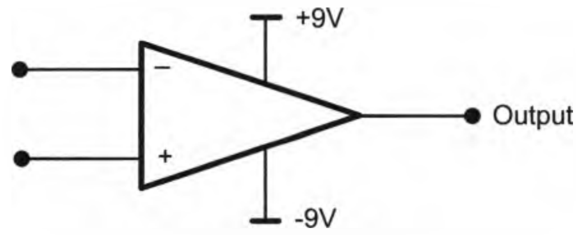


Figure 1

Non-inv. input	Inverting input	Output
1V	500mV	
750mV	1.5V	
-400mV	-700mV	
-2.5V	3V	

11. For the circuit of Figure 2, indicate on the table below whether the output voltage is +15V or -15V given the input voltages specified.

 Tip 1: You'll first need to calculate the potential difference across *R2*. You can do this using Ohm's Law or the Voltage Divider equation.

 Tip 2: Again, be clear about which input is the non-inverting input and which is the inverting input.

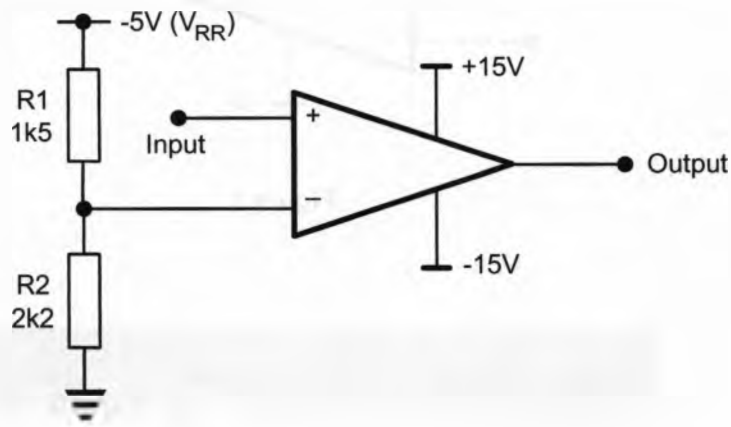


Figure 2

Input Voltage	Output Voltage
3V	
-3V	
-5V	

Section 6 The non-inverting and voltage follower amplifiers

Purpose To develop your ability to predict the output voltage of the non-inverting op amp and voltage follower configurations given the input conditions.

Objectives Once you have completed this section you should be able to:

- Define the terms *negative feedback*, *closed-loop mode*, *closed-loop voltage gain*, and *gain bandwidth product*
- Recognise the non-inverting amplifier and voltage follower op amp configurations in schematic diagrams
- Calculate the closed-loop voltage gain of a non-inverting amplifier given the values of *Rf* and *R1*
- Calculate a value for *Rf* or *R1* for a non-inverting amplifier given its closed-loop voltage gain and the value of the other resistor
- Give typical values of input and output resistance for the non-inverting amplifier
- Calculate the closed-loop bandwidth of a non-inverting amplifier given its closed-loop voltage gain and the op amp's GBWP
- Calculate an op amp's GBWP given a non-inverting amplifier's closed-loop voltage gain and closed-loop bandwidth
- State the voltage gain of the voltage follower
- State the bandwidth of the voltage follower given the op amp's gain bandwidth product
- Specify relative values of input and output resistance for the voltage follower
- Predict the type, magnitude and phase of the output voltage for both configurations given a set of input conditions
- Give applications for both op amp configurations
- Troubleshoot the non-inverting and voltage follower amplifiers
- Use an oscilloscope to measure the voltage gain and bandwidth for both configurations

Introduction

The last chapter introduced you to the op amp and its open-loop mode of operation. This mode of operation restricts the use of the op amp's use to implementing the comparator circuit. A much more versatile mode of op amp operation is the *closed-loop mode* and there are five widely used closed-loop op amp circuits. These are:

- the non-inverting amplifier
- the voltage follower
- the inverting amplifier
- the summing amplifier
- the differencing amplifier (differential amplifier)

In this section we'll look at the first two. We will also look at the effects of negative feedback on op amp performance characteristics including voltage gain, bandwidth and input and output resistances.

Closed-loop op amp operation

In the closed-loop mode of operation, a sample of the op amp's output voltage is fedback to its inverting input which provides negative feedback to the op amp. This reduces the circuit's voltage gain to something more useable in practical applications with the added benefit of improving several of other op amp characteristics like distortion and bandwidth (and, depending on the op amp configuration, the input and output resistances too).

The non-inverting amplifier

Figure 1 shows the circuit of a non-inverting amplifier implemented using an op amp. This amplifier produces a signal at the output that is always bigger than the input voltage and in the same phase.

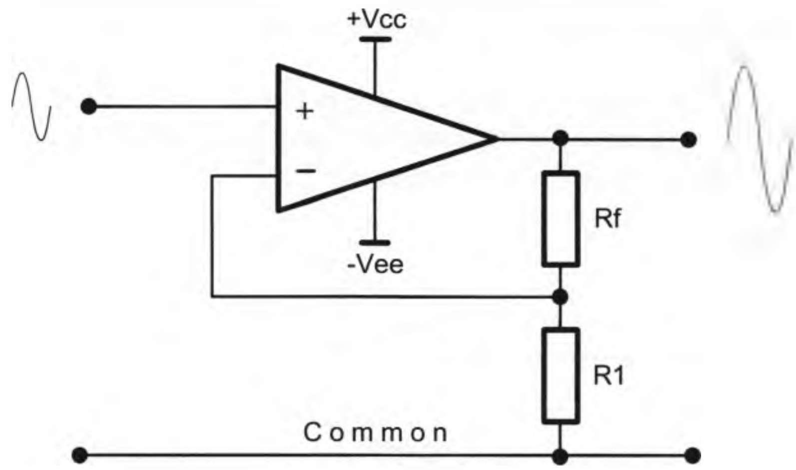


Figure 1 *The non-inverting amplifier*

The upper resistor in the circuit is denoted here as "*Rf*" because it's the resistor that facilitates the negative feedback.

How does negative feedback work in this circuit?
Negative feedback is a bit of a tricky thing to comprehend at first. The following is an explanation of how negative feedback operates in this circuit, the effect on the output voltage, and why the circuit's closed-loop gain is much lower than the op amp's open-loop gain. With that said, there are no assessment questions that check whether you understand what follows so you can skip it and resume reading from the heading "Calculating the voltage gain" if you would prefer. This explanation is provided so that you can see that negative feedback is not magic.

To start, suppose we're talking about the circuit in Figure 2 below with 1V DC connected to the input of a non-inverting amplifier implemented using an op amp with an open-loop gain of 200,000, ±10V supply rails and both resistors are 1kΩ.

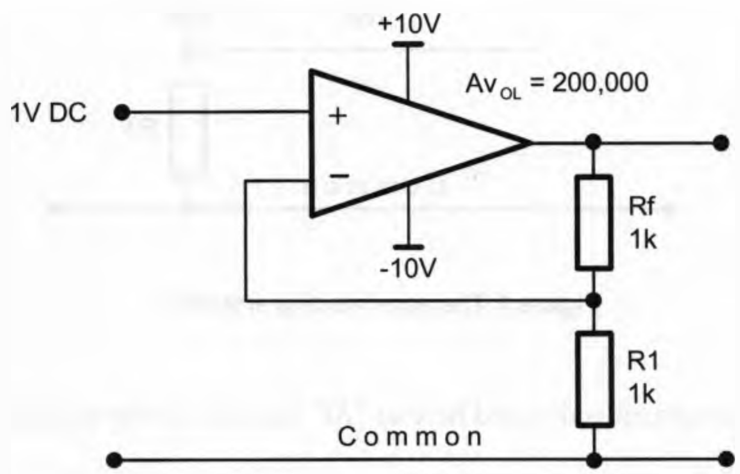


Figure 2

The op amp is off and so we turn it on. As you know from the discussion in Section 5, there must be a difference between the op amp's two inputs and, given the op amp's extremely high gain, this would cause the output to go up to +*Vcc* or -*Vcc* which would be +10V or -10V in this example.

Now, it wouldn't matter which output voltage we use for the following explanation, so let's say the output goes to -*Vcc* or -10V. Using the voltage divider equation, we would find that the voltage on the op amp's inverting pin is -5V [proof: $-10V \times \frac{1k}{1k+1k} = -5V$]. In this way, the circuit is feeding back 50% of the output voltage.

Read those two paragraphs again so that you're clear about the starting position. Have you done that? Ok, here goes...

There's 1V on the op amp's non-inverting pin and -5V on its inverting pin. This means that the non-inverting pin is more positive than the inverting pin and the output wants to change and go up to 1,200,000V [proof: (1V - -5V) × 200,000 = 1,200,000V] (though, of course, it would only go up to +*Vcc* or +10V).

As the output voltage transitions (very quickly but not instantaneoulsy) from -10V towards +10V, it must travel via an infinite number of voltages in between. So, to get to +10V, the op amp's output voltage must travel from -10V to -9.9V to -9.8V to -9V to -8V to -7V and so on. This means that the voltage on the inverting pin would transition (very quickly but not instantaneously) from -5V towards +5V via -4.95V, -4.9V, -4.5V, -4V, -3.5V and so on.

Now here's where things get interesting. As the voltage on the inverting pin does this, the difference in voltage between the op amp's two inputs gets smaller and so the op amp's output heads towards a smaller voltage. For example, if we froze the transition when the op amp's output voltage is -8V, the voltage on the inverting input would be -4V and so the output voltage would be heading towards 1,000,000V instead of 1,200,000V [proof: (1V - -4V) × 200,000 = 1,000,000V].

And if we froze the transition when the op amp's output is +1V, the voltage on the inverting input would be +0.5V and so the output voltage would now only be heading towards 100,000V.

And if we froze the transition when the op amp's output is +1.8V, the voltage on the inverting input would be +0.9V and so the output voltage would now only be heading towards 20,000V.

Can you see what's happening? As the output voltage becomes more positive, the voltage on the op amp's inverting input gets closer to the input voltage and so the op amp's output heads towards a voltage below +*Vcc* that gets smaller and smaller.

Then something truly fascinating happens when the output voltage reaches 1.9999800002V. The voltage on the inverting pin would be 0.9999900001V. So the output voltage would want to be 1.9999800002V [proof: (1V - 0.9999900001V) × 200,000 = 1.9999800002V].

Did you see that?! The op amp's output reaches a voltage that makes the difference between its input produce the output voltage. So, of course, once this happens, the output voltage stops changing and stays at 1.9999800002V (instead of transitioning to +10V as it started off doing).

(I think you should read that last paragraph again!)

Now, I think you'll agree that 1.9999800002V is so close to 2V that we can call it 2V, right? So, putting 1V on the input of this op amp circuit produces an output voltage that is twice as big as the input voltage. So the op amp's circuit's closed-loop gain must be 2. Importantly, this has been set by the value of the resistors. (If we crunched the numbers again using two resistors that are 4kΩ for *Rf* and 1kΩ for *R1*, we would end up with an output voltage extremely close to 5V that we would be able to say that the circuit has a closed-loop gain of 5.)

Calculating the voltage gain of a non-inverting amplifier

The external resistors *Rf* and *R1* "program" the circuit's closed-loop voltage gain and this can be calculated using the equation:

$$\boxed{Av_{CL} = \left(\frac{Rf}{R1}\right) + 1}$$

Note: The "+1" part of the equation means that the amplifier's gain will always be greater than 1 regardless of the values of *R1* and *Rf*.

Let's try an example. What is the closed-loop voltage gain of the amplifier in Figure 2?

$$Av_{CL} = \left(\frac{Rf}{R1}\right) + 1$$

$$Av_{CL} = \left(\frac{1k}{1k}\right) + 1$$

$$Av_{CL} = 2$$

Practise using the equation for yourself by trying the following questions.

1. What is the closed-loop voltage gain of a non-inverting amplifier with a 33kΩ ressistor for *R1* and a 680kΩ for *Rf*?

2. What value of *Rf* is needed to implement a non-inverting amplifier with a gain of 70 if *R1* is a 8k2Ω resistor?

3. What value of *R1* is needed to implement a non-inverting amplifier with a gain of 40 if *Rf* is a 270kΩ resistor?

____

____

____

The non-inverting op amp in real circuits

In the circuit of a television, radio or stereo, there will be dozens resistors or more. So imagine a non-inverting amplifier in such a busy circuit; the two resistors that set its voltage gain are not going to be labelled *Rf* and *R1*! They could be *R405* and *R406*, or *R23* and *R41*, or other numbers. Moreover, there will be other resistors in the schematic diagram near the op amp.

As a technician, you're expected to be able to take the general equation and apply it to a specific circuit. This means you will need to be able to identify which two resistors in the circuit are the *Rf* and *R1* resistors. To help you do that, remember that the "*f*" in *Rf* stands for feedback. So the *Rf* resistor is always the one that is connected between the op amp's output and its inverting input. The *R1* resistor is always the resistor that is connected between both *Rf* and the op amp's inverting input and common (or earth).

Non-inverting amplifier characteristics

Recall that the last chapter discussed the amplifier characteristics that are said to be important and these include: gain, bandwidth, input resistance, output resistance and distortion. Let's consider these for the non-inverting amplifier.

- Gain - the closed-loop voltage gain (Av_{CL}) is lower than the open-loop voltage gain (Av_{OL}) of the op amp and is set by *Rf* and *R1*.

- Bandwidth - the closed-loop bandwidth (BW_{CL}) is higher than the open-loop bandwidth (BW_{OL}) of the op amp and is affected by the amplifier's gain (we'll look at this characteristic in more detail later in this chapter).

- Input resistance - this is much higher than the input resistance of the op amp operated in the open-loop mode (which is already quite high). Values easily exceed 10MΩ and can even be several Giga ohms.

- Output resistance - this is lower than the output resistance of the op amp operated in the open-loop mode and is typically less than 100Ω.

- Distortion - this is lower than the distortion of the op amp operated in the open-loop mode.

You now know how to calculate the non-inverting amplifier's closed-loop voltage gain and the following notes will show you how to calculate its closed-loop bandwidth. It's also possible to calculate closed-loop values for input resistance, output resistance and distortion but this is beyond what is expected of you for this Unit.

A minor design variation of the non-inverting amplifier

The circuit in Figure 3 below shows a minor variation on the basic non-inverting amplifier. You'll notice that an extra resistor (*R2*) is connected between the circuit's input and common.

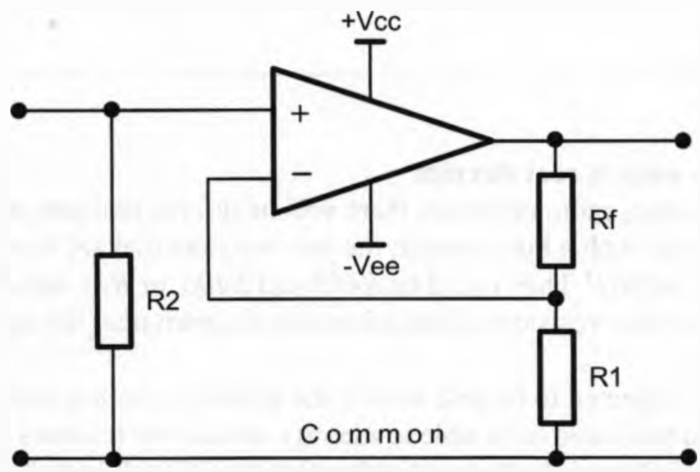


Figure 3 *Non-inverting amplifier with a resistor connected between the input and common*

The extra resistor is needed to ensure that the op amp works reliably in situations when the non-inverting amplifier might be operated without an input voltage.

To explain, in normal operation an op amp has tiny currents flowing in or out of both of its inputs (in the order of tens of nano amps). If there is no path for these currents to flow, the op amp's operation becomes unreliable. This situation can arise for non-inverting amplifiers if there is no input connected. So, the extra resistor (*R2*) is used to provide an alternative path for the non-inverting input's currents if this happens.

The inclusion of *R2* has no effect on the circuit's voltage gain. Unfortunately, *R2* does lower the circuit's input resistance because it is connected in parallel with the op amp's input resistance and, as you know, the total resistance of resistors connected in parallel is lower. However, this problem can be minimised by making *R2* a fairly large value (for example, 1MΩ or bigger).

The voltage follower (also known as the buffer)

Figure 4 shows the circuit of a voltage follower amplifier. It's basically the non-inverting amplifier circuit discussed earlier but with 100% negative feedback (that is, all of the output voltage is fedback to the op amp's inverting pin). This op amp configuration produces a signal at the output that is almost identical to the input voltage and in the same phase. This is why the circuit is called a voltage follower (that is, the output "follows" the input).

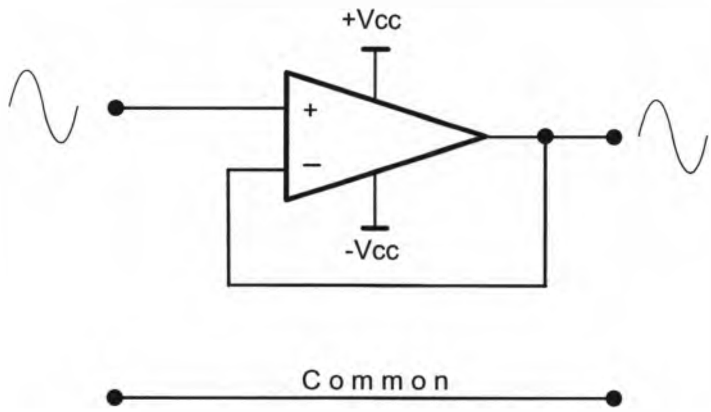


Figure 4 *Voltage follower amplifier or Buffer*

$$Av = 1 \text{ or } 0\text{dB}$$

Voltage follower characteristics

- Gain - the closed-loop voltage gain (Av_{CL}) of the buffer is the lowest of all the closed-loop op amp configurations and is 1.
- Bandwidth - the closed-loop bandwidth (BW_{CL}) of the buffer is the widest of all the op amp configurations and is equal to the op amp's GBWP (more next).
- Input resistance - this is much higher than the input resistance of the op amp operated in the open-loop mode (which is already quite high) and is the highest of the op amp configurations.
- Output resistance - this is lower than the output resistance of the op amp operated in the open-loop mode and is the lowest of the op amp configurations.
- Distortion - this is lower than the distortion of the op amp operated in the open-loop mode and is the lowest of the op amp configurations.

The voltage follower as a "buffer" circuit

Buffering of amplifiers is a common application for the voltage follower circuit. To explain, consider the example of an amplifier connected to a load in Figure 5 below. As the diagram shows, the unloaded output voltage is 2V, however, the loaded output voltage is only 0.667V. This occurs because of the load low resistance relative to the amplifier's output resistance.

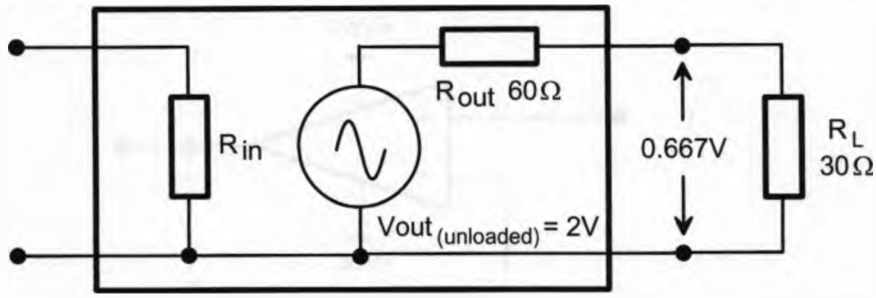


Figure 5 *An amplifier connected to a load*

If the circuit is changed so that the amplifier in Figure 5 is connected to the load via a voltage follower, the voltage across the load increases dramatically even though the voltage follower only has a gain of 1 (see Figure 6).

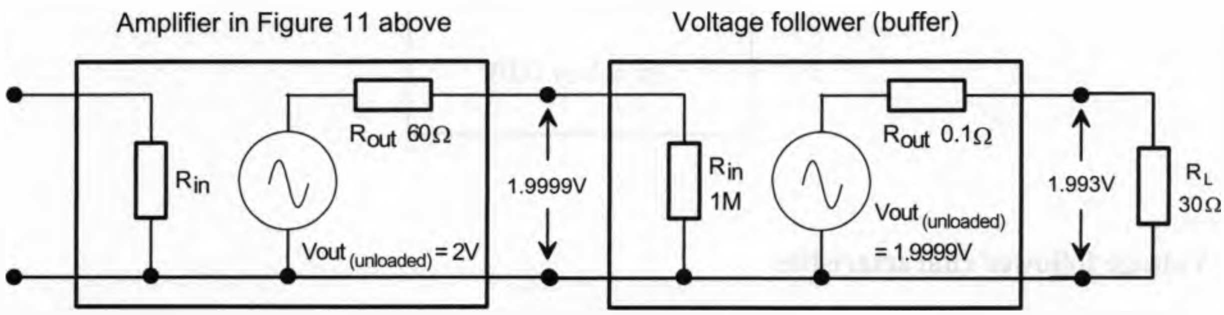


Figure 6 *The amplifier in Figure 5 connected to its load by a voltage follower*

The voltage follower's almost ideal input and output characteristics are responsible for this improvement. The input resistance of a voltage follower is extremely high (1MΩ is shown in Figure 6 above but it would be much bigger than this) and so the amplifier's loaded output voltage is only fractionally less than its unloaded output voltage. At the same time, the output resistance of a voltage follower is extremely low so the load resistor doesn't load the voltage follower's output voltage.

As you will see, this practice of using buffer circuits like this is used extensively in electronics equipment.

The frequency performance of op amp circuits

As already mentioned, the bandwidth of an op amp operated in the open-loop mode is about 10Hz (but this will be a little different from one op amp and another). Specifically, the op amp's frequency response looks like that shown in Figure 7 below.

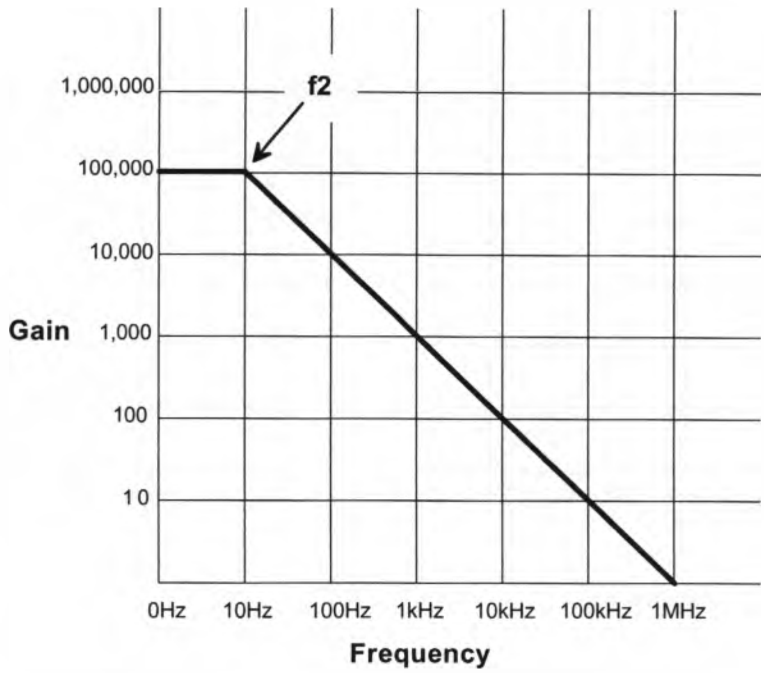


Figure 7 *The frequency response graph of an op amp operating in open-loop mode*

As you can see from the graph in Figure 7, op amps have an *f2* but not an *f1*. This means that they can amplify low frequency signals and DC voltages. Notice also that the frequency response of op amps beyond the *f2* is fairly typical of general amplifier frequency response discussed earlier (though, this is true only of *frequency compensated* op amps).

Recall that one of the benefits of introducing negative feedback into op amps is an increase of the bandwidth. So, the non-inverting op amp circuit, the buffer, and all other op amp circuits with negative feedback have a bandwidth that is much better than 10Hz. The reason for this is complex and beyond the scope of this unit so we won't deal with it here (you'll be taught more about negative feedback for a later unit).

Gain bandwidth product (GBWP or UGBP)

The open-loop frequency response graph of an op amp can be used to work out the op amp's closed loop frequency response. Figure 8a shows that the *f2* of an op with a voltage gain of 1,000 is 1kHz and Figure 8b shows that the *f2* of an op amp with a voltage gain of 10 is 100kHz.

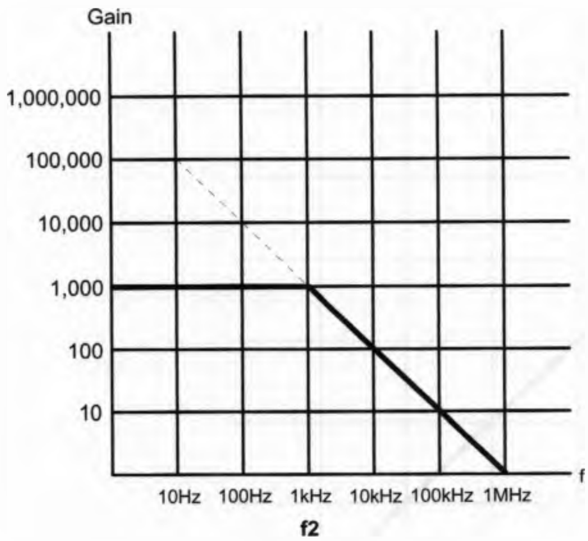


Figure 8a

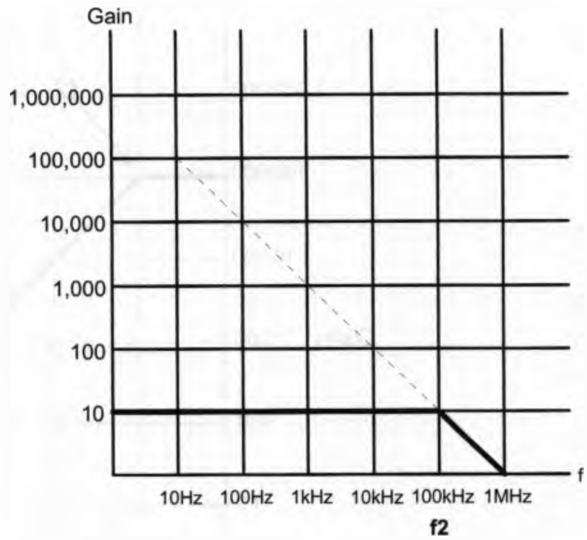


Figure 8b

Finding the *f2* of an op amp by graphical means like this is both time consuming and a little inaccurate if the closed-loop gain is not exactly 10, 100 or 1000 and so on. Fortunately, there's another way to find the *f2* and bandwidth of a closed-loop op amp circuit. If you look at the op amp's roll-off you'll notice that it is a perfectly straight line (or linear). Because of this, if the op amp's voltage gain is multiplied by its *f2* for any value of gain, the answer is always the same number.

To prove the point, for Figure 8a the gain is 1,000 and the *f2* is 1kHz so the product is 1,000,000. And, for Figure 8b the gain is 10 and the *f2* is 100kHz so the product is also 1,000,000.

Manufacturer's of op amps understand this and so they provide this figure in their specifications and call it either the *gain bandwidth product* (GBWP) or the *unity gain bandwidth product* (UGBP). As its name implies, the equation for GBWP is:

$$\boxed{GBWP = Av_{CL} \times BW_{CL}}$$

Where
Av_{CL} is the op amp's closed-loop voltage gain
BW_{CL} is the op amp's closed-loop bandwidth

This equation will work where Av_{CL} is a positive number. For inverting amplifiers where the gain is negative, leave off the negative sign (otherwise you will end up with a negative bandwidth which is impossible).

Let's try an example. What is the *GBWP* of a non-inverting amplifier with a bandwidth of 160kHz and a closed-loop voltage gain of 25?

$$GBWP = Av_{CL} \times BW_{CL}$$

$$= 25 \times 160kHz$$

$$= 4MHz$$

As the *GBWP* is given to you by the manufacturer, technicians are more likely to be using it to find the op amp's closed-loop bandwidth for a particular value of gain or to find the gain of an op amp circuit for a particular value of closed-loop bandwidth. To do so, simply transpose the equation to make the variable that you're looking for the subject. Let's try an example.

What is the closed-loop bandwidth of a non-inverting amplifier with a *GBWP* of 1MHz and a closed-loop voltage gain of 10?

$$BW_{CL} = \frac{GBWP}{Av_{CL}}$$

$$= \frac{1{,}000{,}000Hz}{10}$$

$$= 100kHz$$

[Note: These *GBWP* calculations only work for op amps that are internally *frequency compensated*. Uncompensated op amps are more difficult to deal with and are covered in more advanced units.]

Practise finding bandwidth and voltage gain using the GBWP by trying the following questions for yourself.

1. Calculate the closed-loop bandwidth of a non-inverting amplifier with a closed-loop voltage gain of 20 and implemented using an op amp with a GBWP of 750kHz.

2. Calculate the closed-loop voltage gain of a non-inverting amplifier with a closed-loop bandwidth of 3.5kHz if the op amp has a GBWP of 1.25MHz.

3. What is the closed-loop bandwidth of a voltage follower if it is implemented using an op amp having a GBWP of 4MHz?

Troubleshooting non-inverting op amp configurations

When trying to locate the specific cause of a fault with op amps circuits with negative feedback (like the non-inverting and voltage follower amplifiers), the first thing you must always do is check the power supply rails. Recall that op amps with dual rail supply have both a plus and minus power supply voltage ($\pm Vcc$) that should be the same. Op amps with a single rail supply have a plus voltage rail ($+Vcc$) and a zero volt rail.

Once you've checked the supply rails, there's a marvellously simple test you can perform that will give you clues about where the problem might lie.

If you read that explanation of how negative feedback works (on page 6-4 and 6-5), you'll know that the difference between the op amp's two inputs is extremely small. In fact, the difference is so small that conventional measuring instruments cannot measure it. In other words, the difference is effectively 0V. (Even if you didn't read that explanation, you can still just accept this as a fact for our purpose here.)

This means that, if you measure the voltage on the op amp's two inputs with respect to common they must be the same as each other. This is illustrated in Figure 9 below using a non-inverting amplifier with a 1V DC input but the same is true for the voltage follower.

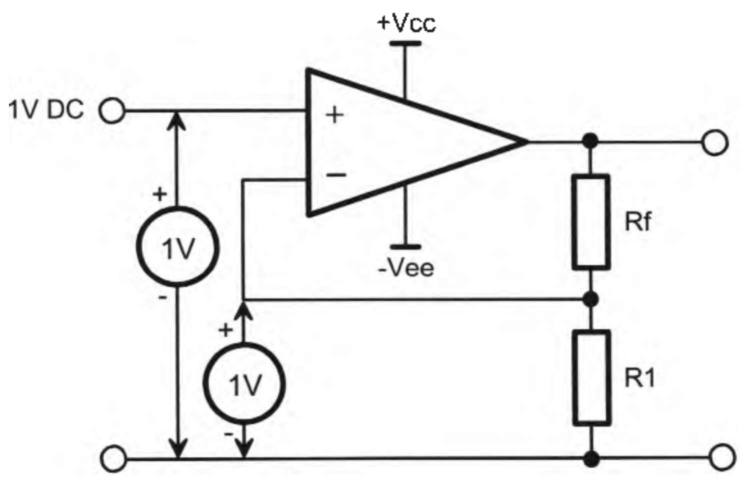


Figure 9 *The voltage on the op amp's two inputs in a non-inverting amplifier circuit are the same as each other (and the input) because the potential difference between them is effectively 0V*

Knowing this gives us a simple but fabulously useful trick for troubleshooting the non-inverting and voltage follower amplifiers that you suspect are faulty (and other op amp configurations too!). Simply measure the op amp's non-inverting and inverting inputs with respect to common as shown in Figure 9.

If the two inputs have exactly the same voltage, and they're the same as the input voltage, then this tells you that negative feedback must be operating in the circuit. So this also tells you that the op amp is working and that the feedback resistor (*Rf*) is not open-circuit. In which case, the only possible problems with the circuit are: one of the two resistors has changed value, or *R1* has gone open-circuit, or there's no input signal (perhaps due to a cracked PCB track or dry-joint).

However, if the two inputs are not exactly the same voltage then this tells you that negative feedback is not operating in the circuit. In which case, possible problems include: the op amp may be faulty, or the feedback resistor is open-circuit, or the loop is broken for some other reason (perhaps due to a cracked PCB track or dry-joint).

Words that may be new to you

Gain bandwidth product	A constant that allows you to work out the bandwidth of an amplifier for a given value of gain (and vice versa).
GBWP	Abbreviation for gain bandwidth product.
Non-inverting amplifier	A closed-loop op amp configuration where the output voltage is always in phase with the input voltage.
Voltage follower	A non-inverting amplifier with 100% negative feedback and so its closed-loop voltage gain is always one (1). Amplifiers with a gain of one are often said to have "unity" gain.
UGBP	Abbreviation for unity gain bandwidth but is the same as the gain bandwidth product.

Student notes

Skill practice 6

Practise measuring the voltage gain and bandwidth of amplifier circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- Emona Trainer (or a prototyping breadboard)
- DMM
- TL071
- 22kΩ ¼W resistor
- 120kΩ ¼W resistor
- 220kΩ ¼W resistor
- three BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ________________ ________________ ________________	Move bags and other objects from walkways Plan lifting of equipment Other: ________________ ________________ ________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ________________ Date: ________________

Part A - The non-inverting amplifier

2. Gather the equipment needed for this exercise.

3. Connect the circuit of Figure 1 on the Emona Trainer

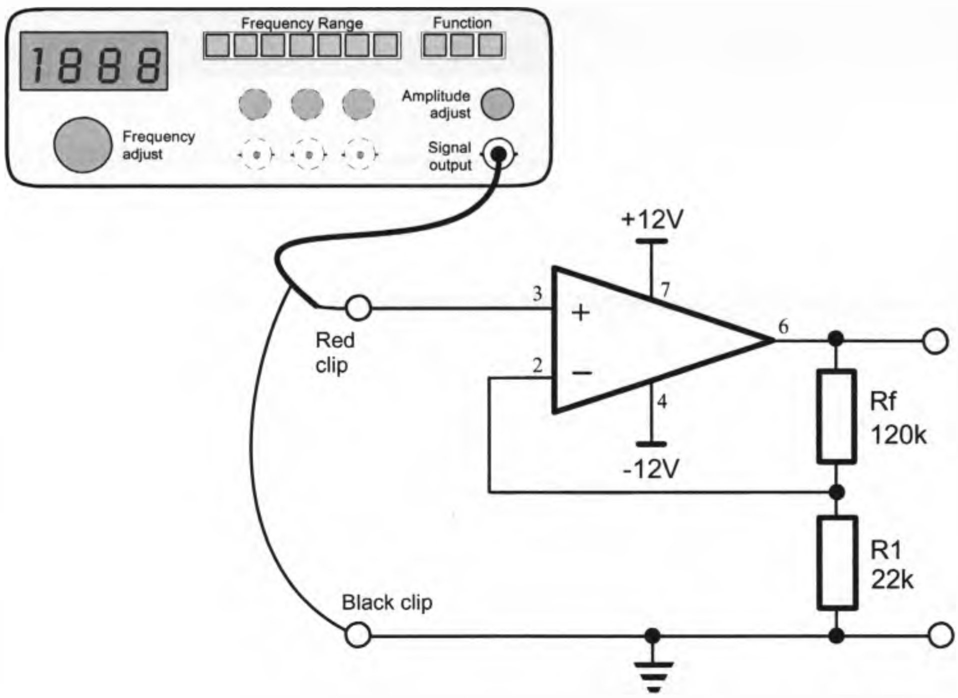


Figure 1

4. Calculate the amplifier's theoretical voltage gain using the equation $Av = (\frac{Rf}{R1}) + 1$. Record this value in Table 1 (on the next page).

5. Calculate and record the amplifier's theoretical output for a 500mVpp AC input.

6. Connect the CRO's channel 1 input to the amplifier's input.

7. Adjust the amplifier's input signal for a 500mVpp 1kHz sinewave.

8. Connect the CRO's channel 2 input to the amplifier's output and adjust the CRO to observe both the input and output signals at the same time.

9. Check that the output voltage is not clipping.

Note: If it is, reduce the input voltage and record the new *Vin* value in Table 1.

10. Measure and record the amplifier's output voltage.

11. Calculate and record the actual gain of the amplifier using the equation $Av = \frac{Vout}{Vin}$ and your measured values of *Vin* and *Vout*.

Table 1

Theoretical Av (Step 4)	**Vin**	**Theoretical Vout** (Step 5)	**Measured Vout** (Step 10)	**Actual Av** (Step 11)
	500mVpp			

Question 1
How do the theoretical and measured voltage gains compare? What might explain any differences?

____

____

____

Question 2
What is the phase relationship between the input and the output?

____

12. Simulate a fault condition where the feedback resistor has gone open-circuit by removing it from the circuit.

13. Briefly describe what happened to the output voltage.

____

____

Question 3
Why did removing the feedback resistor have this effect?

____

____

____

14. Reconnect the feedback resistor.

15. Simulate a fault condition where *R1* has gone open-circuit by removing it from the circuit.

16. Briefly describe what happened to the output voltage.

Question 4
Why did removing *R1* have this effect?

The teacher needs to check your work at this point...

Part B - Gain and bandwidth

17. Reconnect *R1* and check that the circuit is operating as it should.

18. Disconnect the function generator and CRO from the circuit but leave the rest of the circuit intact.

19. Connect the bench-mounted DC power supply to the circuit as shown in Figure 2 below.

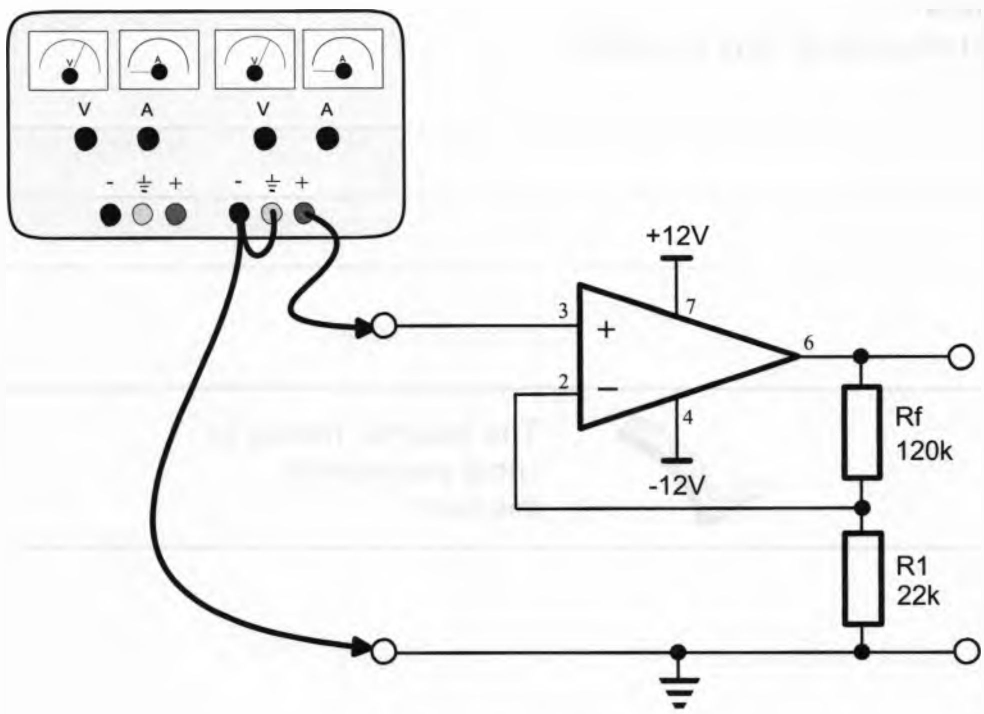


Figure 2

20. Adjust the bench-mounted DC power supply's right-hand side output to 0.5V. **Note:** Measure this with a DMM - don't trust the supply's analog meter.

21. Measure the amplifier's output voltage and record your measurement in the space provided below.

   Vout = ______________________________

Question 5
What does this output voltage tell us about the amplifier's low frequency response?

____

____

Question 6

That being the case, what does this tell us about the amplifier's *f2* and its bandwidth?

____

____

____

The teacher needs to check your work at this point...

22. Disconnect the DC power supply but leave the rest of the circuit intact.

23. Reconnect the function generator and CRO to the circuit (connect the CRO's channel 1 to the amp's input and channel 2 to its output).

24. Find by measurement the amplifier's upper frequency roll-off point (*f2*) and record this value in Table 2 below.

    Note: If you're not sure how to find *f2*, refer to the instructions on page 3-25.

25. Use the amplifier's gain and its *f2* to determine and record the op amp's *GBWP*.

26. Change *Rf* from a 120kΩ resistor to a 220kΩ resistor.

27. Return the input signal to 1kHz.

28. Check *Vout* to make sure that it's not clipped.

29. Find by measurement the amplifier's upper frequency roll-off point (*f2*) and record this value in Table 2.

Table 2

f2 (Step 24)	**GBWP** (Step 25)	*f2* (Step 29)

Question 7

Use the amplifier's *GBWP* and new *f2* to calculate the circuit's new voltage gain.

____

____

Question 8

Calculate the circuit's new theoretical voltage gain using: $Av = (\frac{Rf}{R1}) + 1$.

____

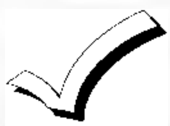
____

Question 9

How do the two calculated gains compare? What might explain any differences?

____

____



The teacher needs to
check your work at
this point...

Part C - The voltage follower

30. Dismantle the non-inverting amplifier and connect the circuit of Figure 3.

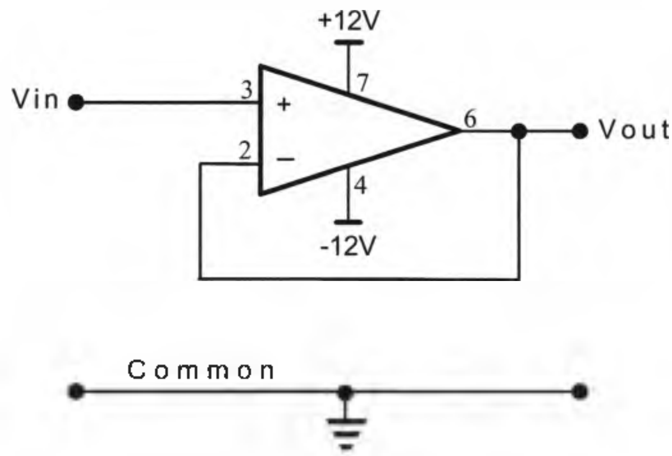


Figure 3

31. Write the amplifier's theoretical gain in Table 3 below.

32. Calculate and record the amplifier's theoretical output voltage for a 2Vpp AC input.

33. Connect the function generator to the amplifier's input.

34. Connect the CRO's channel 1 input the amplifier's input.

35. Adjust the function generator for a 2Vpp 1kHz sinewave.

36. Connect the CRO's channel 2 input to amplifier's output and adjust the CRO so that you see both the input and output signals at the same time.

37. Measure and record the amplifier's output voltage.

38. Calculate and record the actual gain of the amplifier using the equation $Av = \frac{Vout}{Vin}$ and your measured values of *Vin* and *Vout*.

Table 3

Theoretical Av	Vin	Theoretical Vout	Measured Vout	Actual Av
	2Vpp			

Question 10
What is the phase relationship between the input and the output?

Question 11
Why does this circuit have the phase relationship that you have observed?

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 9 refer to Figure 1

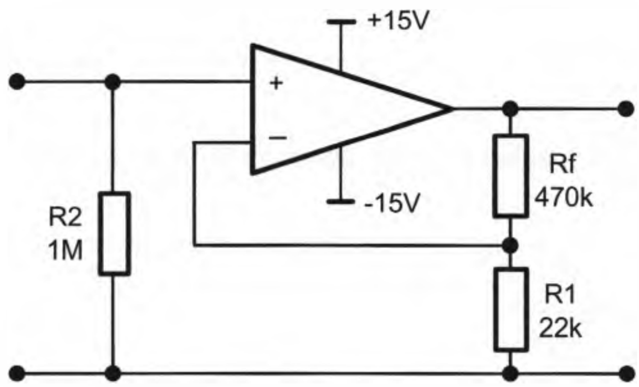


Figure 1

1. What type of closed-loop op amp configuration is this circuit?

2. Calculate the circuit's voltage gain.

3. What is the phase relationship between input and output?

4. What is the maximum peak-to-peak output voltage before clipping would occur?

5. Calculate the maximum input voltage before clipping would occur at the output.

6. What is the input resistance?

7. Calculate the circuit's bandwidth if the op amp's GBWP is 3MHz.

8. What is the voltage on the inverting input if the input voltage is 2V DC?

9. What would you expect to observe at the output while a sinewave is connected to the input if the feedback resistor went open-circuit?

Questions 10 to 17 refer to Figure 2

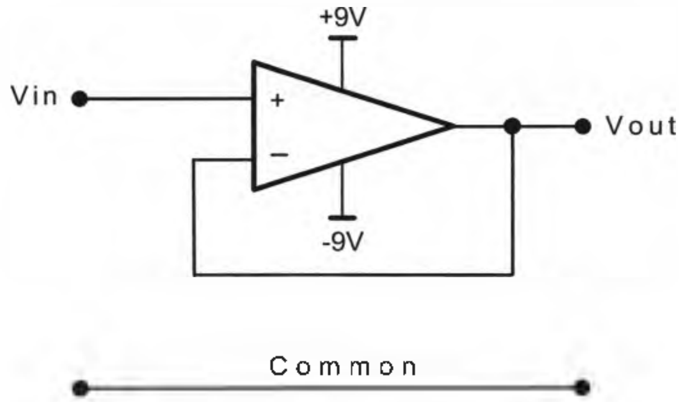


Figure 2

10. What type of closed-loop op amp configuration is this circuit?

____

11. What is the circuit's gain?

____

12. What is the phase relationship between input and output?

____

13. What is the maximum peak-to-peak output voltage before clipping would occur?

____

14. What is the maximum input voltage before clipping would occur at the output?

____

____

15. What is the circuit's input resistance?

16. What is the amplifier's bandwidth if the GBWP is 2.5MHz?

17. What is the voltage on the inverting input if the input voltage is 2V?

For the following fault-finding questions, assume in each case that the power supply has been checked and found to be ok.

18. Figure 3 below shows a faulty non-inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty and what's wrong with it. **Tip:** Work out what the circuit's output voltage should be.

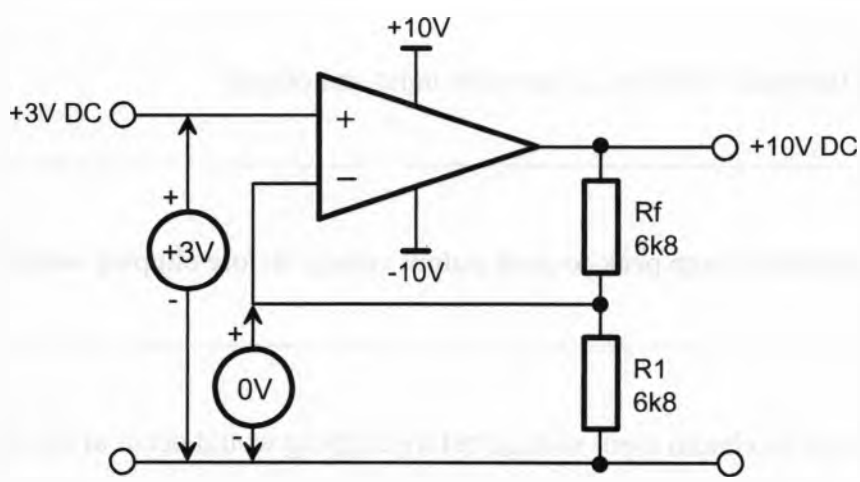


Figure 3

19. Justify your answer to Q18 in terms of how the measurements in the circuit support your conclusion.

20. Figure 4 below shows a faulty non-inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty and what's wrong with it.

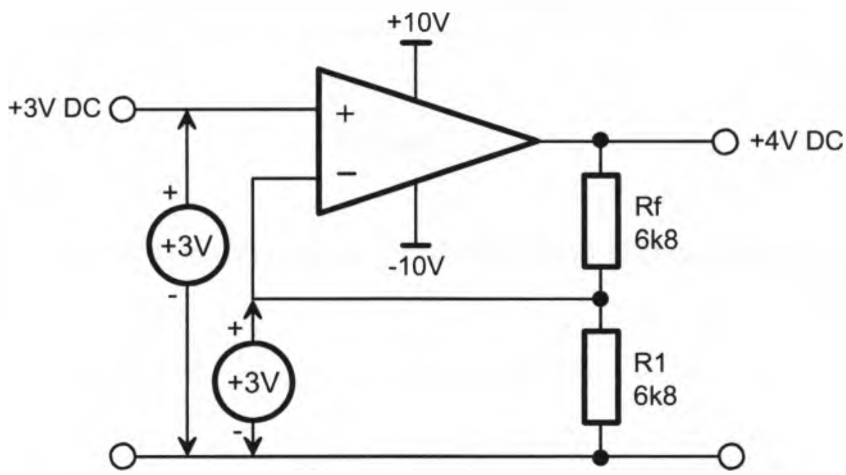


Figure 4

21. Justify your answer to Q20 in terms of how the measurements in the circuit support your conclusion.

22. Figure 5 below shows a faulty non-inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty.

____

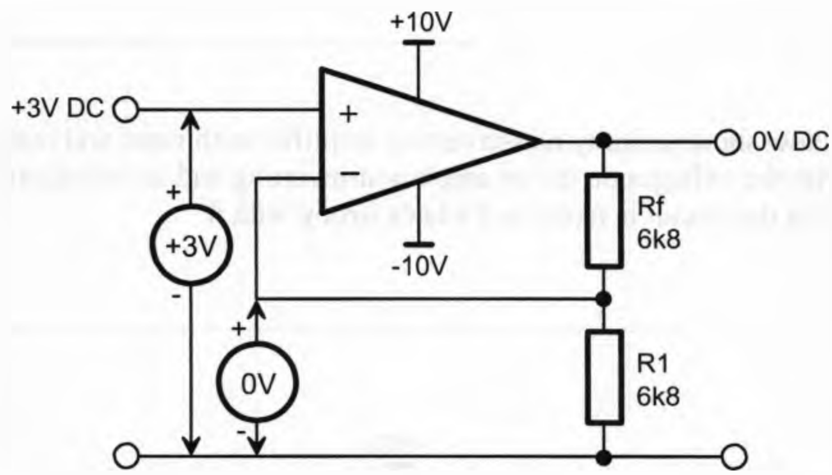


Figure 5

23. Justify your answer to Q22 in terms of how the measurements in the circuit support your conclusion.

____

____

____

____

24. Figure 6 below shows a faulty non-inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty and what's wrong with it.

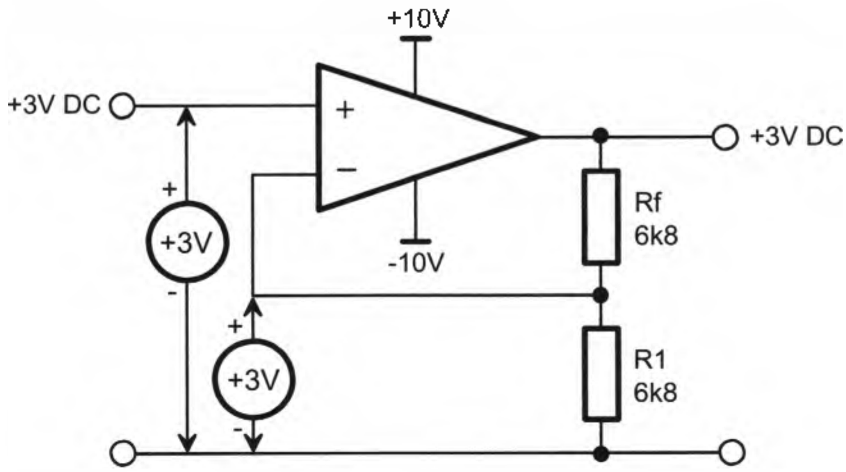


Figure 6

25. Justify your answer to Q24 in terms of how the measurements in the circuit support your conclusion.

Student notes

Section 7 The inverting and summing amplifiers

Purpose To develop your ability to predict the output voltage of the the inverting and summing amplifier op amp configurations given the input conditions.

Objectives Once you have completed this section you should be able to:

- Recognise the inverting and summing op amp configurations in a schematic diagram
- Calculate the closed-loop voltage gain of an inverting amplifier given the values of *Rf* and *Rin*
- Calculate a value for *Rf* or *Rin* for an inverting amplifier given its closed-loop voltage gain the value of the other resistor
- Calculate the closed-loop bandwidth of an inverting amplifier given its closed-loop voltage gain and the op amp's GBWP
- Calculate an op amp's GBWP given an inverting amplifier's closed-loop voltage gain and closed-loop bandwidth
- Give typical values of input and output resistance for the inverting amplifier configuration
- Give applications for the inverting op amp configuration
- Predict the type, magnitude and phase of the output voltage for the inverting and summing amplifier configurations given a set of input conditions
- Give applications for the summing op amp configuration
- Troubleshoot the inverting and summing amplifiers
- Verify the operation of both configurations

Introduction

In this section we'll be looking at two more commonly used op amp configurations; the inverting amplifier and the summing amplifier (which is a circuit that's based on the inverting amplifier).

The inverting amplifier

Figure 1 shows the circuit of an inverting amplifier. This amplifier produces a signal at the output that can be bigger or smaller than the input voltage and phase inverted.

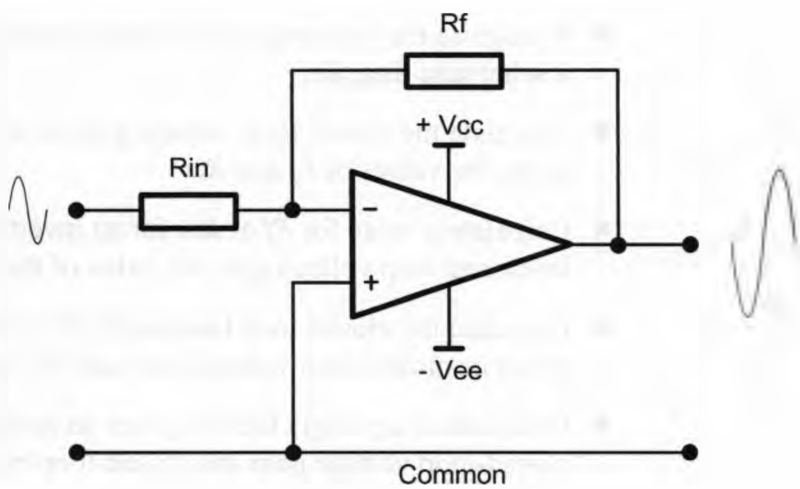


Figure 1 *The inverting amplifier*

Calculating the voltage gain of an inverting amplifier

Like the non-inverting amplifier, two external resistors - *Rf* and *Rin* - set the circuit's closed-loop voltage gain and this can be calculated using the equation:

$$\boxed{Av_{CL} = -\left(\frac{Rf}{Rin}\right)}$$

The minus sign indicates that the output voltage is phase inverted

Notice that this equation is **similar but different** to the closed-loop voltage gain equation for the non-inverting amplifier.

Let's try an example. What is the amplifier's closed-loop voltage gain in Figure 1 if *Rin* = 10kΩ and *Rf* = 100kΩ?

$$Av_{CL} = -(\tfrac{Rf}{R1})$$

$$Av_{CL} = -(\tfrac{100k}{10k})$$

$$Av_{CL} = -10$$

Practise using the equation for yourself by trying the following questions.

1. What is the closed-loop voltage gain of an inverting amplifier with an 18kΩ resistor for *Rin* and a 270kΩ resistor for *Rf*?

2. What value of *Rf* is needed to implement an inverting amplifier with a gain of -50 if *Rin* is a 6kΩ resistor?

3. What value of *Rin* is needed to implement an inverting amplifier with a gain of -90 if *Rf* is a 560kΩ?

The inverting op amp in real circuits
The two resistors that set the gain of a inverting amplifier in a real circuit are not going to be labelled *Rf* and *Rin*. As real circuits will have many components, these two resistors could be labelled *R60* and *R61* or other numbers. Moreover, there will be other resistors in the schematic diagram near the op amp.

As a technician, you're expected to be able to take the general equation and apply it to a specific circuit. This means you will need to be able to identify which two resistors in the circuit are the *Rf* and *Rin* resistors. To help you do that, remember that the "*f*" in *Rf* stands for feedback. So the *Rf* resistor is always the one that is connected between the op amp's output and its inverting input. The *Rin* resistor is always the resistor that is connected between both *Rf* and the op amp's inverting input and the source.

Inverting amplifier characteristics

- Gain - the closed-loop voltage gain (Av_{CL}) is lower than the open-loop voltage gain (Av_{OL}) of the op amp and is set by *Rin* and *Rf*.

- Bandwidth - the closed-loop bandwidth (BW_{CL}) is higher than the open-loop bandwidth (BW_{OL}) of the op amp and is affected by the amplifier's gain.

- Input resistance - this is lower than the input resistance of the op amp operated in the open-loop mode (which is not good for voltage amplifiers) and is the same as *Rin*. This is because the signal source is connected to the amplifier via *Rin*. The other end of *Rin* is "virtual earth" so *Rin* is all that the source "sees" when "looking into" the amplifier.

- Output resistance - this is lower than the output resistance of the op amp operated in the open-loop mode and is typically less than 100Ω.

- Distortion - this is lower than the distortion of the op amp operated in the open-loop mode.

You now know how to determine the inverting amplifier's input resistance and calculate its closed-loop voltage gain. The notes on the next page show you how to calculate its closed-loop bandwidth (its just the same as for the non-inverting amplifier). It's also possible to calculate closed-loop values for output resistance and distortion but this is beyond what is expected of you for this Unit.

Calculating bandwidth

All op amps have a gain bandwidth product (GBWP) which is a constant that can be used to determine the bandwidth of closed-loop op amp configurations. This is explained in Section 6 and the notes showed how to use the GBWP for calculating the bandwidth of the non-inverting and voltage follower amplifiers. Recall that the closed-loop bandwidth is found using the equation: $BW_{CL} = \frac{GBWP}{Av_{CL}}$.

Importantly, as the inverting amplifier is a closed-loop op amp circuit, the equation can be used to find its closed-loop bandwidth too but with one minor modification. Inverting op amps have phase inversion and this is denoted by simply appending a minus sign in front of the gain figure when expressed as a ratio. The minus sign must be dropped when calculating closed-loop bandwidth.

1. Calculate the closed-loop bandwidth of an inverting amplifier with a closed-loop voltage gain of -150 and implemented using an op amp with a GBWP of 4MHz.

Practical limitations of the inverting amplifier

Ideally, the *Rin* of inverting amplifiers should be a large value to make the circuit's input resistance as large as possible. However, there is a limit to how big it can be. Suppose you wanted to have an amplifier with an input impedance of 1MΩ and a gain of 100. A 1MΩ resistor for *Rin* is not a problem but *Rf* would have to be a 100MΩ resistor. Such high value resistors as this are typically more expensive than lower value resistors. Moreover, surface contamination of high value resistors (dust, grease, solder flux, etc) can alter their effective resistance over time in a manner that doesn't happen to lower value resistors.

At the same time, the value of *Rin* affects the noise performance of the op amp. The bigger *Rin* the more noise the circuit produces. In practice, *Rin* needs to be 20kΩ or less to keep the noise at an acceptable level. Another practical problem with the inverting amplifier is that sometimes we don't want the output to be phase inverted. All of these problems can be avoided by using the non-inverting op amp circuit.

The Summing amplifier

The summing amplifier is an inverting amplifier with two or more inputs. An example is shown in Figure 2 below. As the name suggests, its output is the addition (sum) of the possible output voltages produced by each of the inputs. You might know of the same kind of amplifier by its other popular name; the mixer.

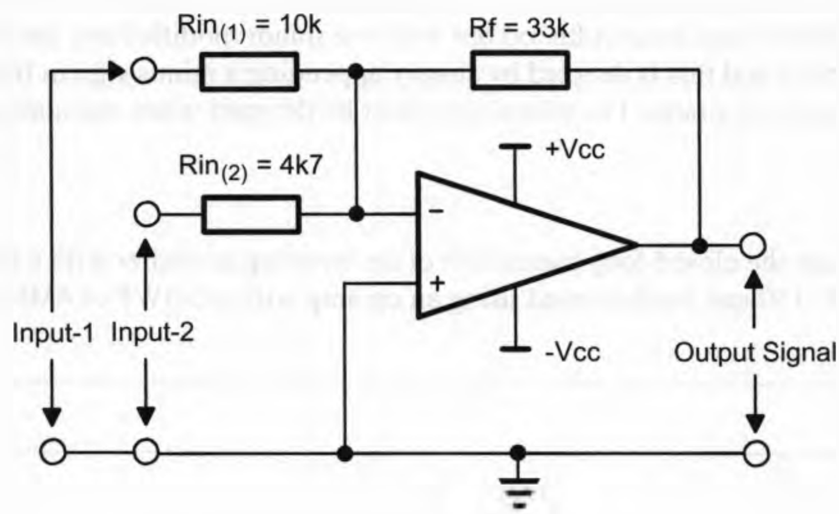


Figure 2 *A two-input summing amplifier*

To best understand the operation of this circuit, it can be thought of as two individual inverting amplifiers.

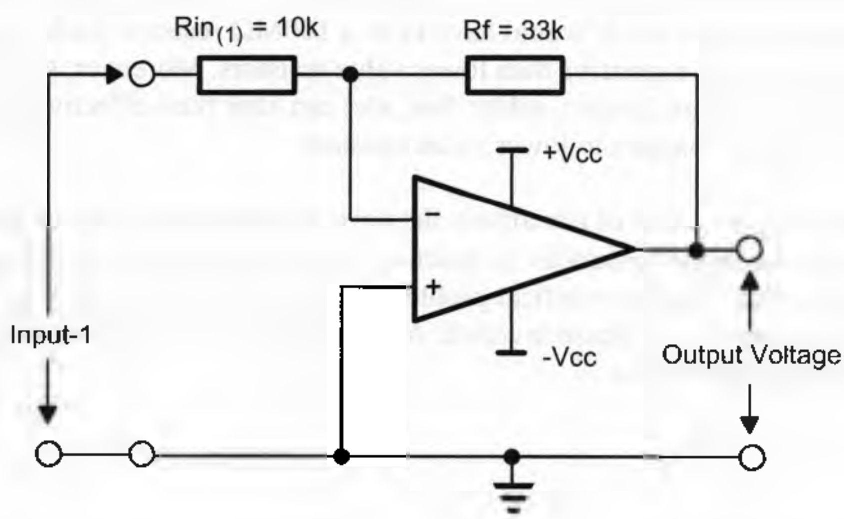


Figure 3 *The summing amp circuit in Figure 2 can be thought of as being this amplifier*

If we thought of the summing amplifier in Figure 2 as just a single input inverting amplifier consisting of the 10kΩ and 33kΩ resistors (per Figure 3 on the previous page) we can easily find the output voltage due to this input provided we know *Vin*.

For example:

$$Av_{(1)} = -\left(\frac{Rf}{Rin_{(1)}}\right)$$

$$Av_{(1)} = -\left(\frac{33k\Omega}{10k\Omega}\right)$$

$$Av_{(1)} = -3.3$$

And, if $Vin_{(1)}$ is 500mV then *Vout* due to $Vin_{(1)}$ is:

$$Vout = Av \times Vin_{(1)}$$

$$Vout = -3.3 \times 500mV$$

$$Vout = -1.65V$$

Similarly, if we thought of the summing amplifier in Figure 2 as just a single input inverting amplifier consisting of the 4k7Ω and 33kΩ resistors (per Figure 4 below) we can find the output voltage due to this input provided we know *Vin*.

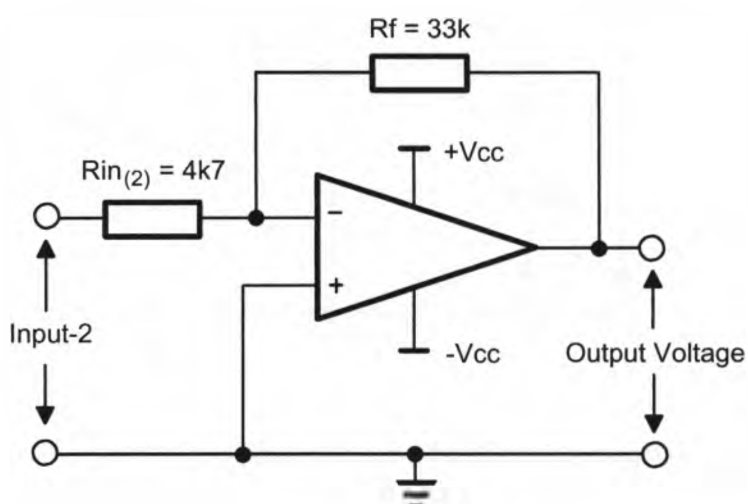


Figure 4 *The summing amp circuit in Figure 2 can also be thought of as being this amplifier*

For example:

$$Av_{(2)} = -\left(\frac{Rf}{Rin_{(2)}}\right)$$

$$Av_{(2)} = -\left(\frac{33k\Omega}{4k7\Omega}\right)$$

$$Av_{(2)} = -7$$

And, if $Vin_{(2)}$ = 300mV then *Vout* due to $Vin_{(2)}$ is:

$$Vout = Av_{(2)} \times Vin_{(2)}$$

$$Vout = -7 \times 300mV$$

$$Vout = -2.1V$$

Now, if 500mV is connected to *Input-1* at the same time as 300mV is connected to *Input-2* (per Figure 5 below) then the output voltage would be the sum or addition of the output voltages that would be produced for each input on its own.

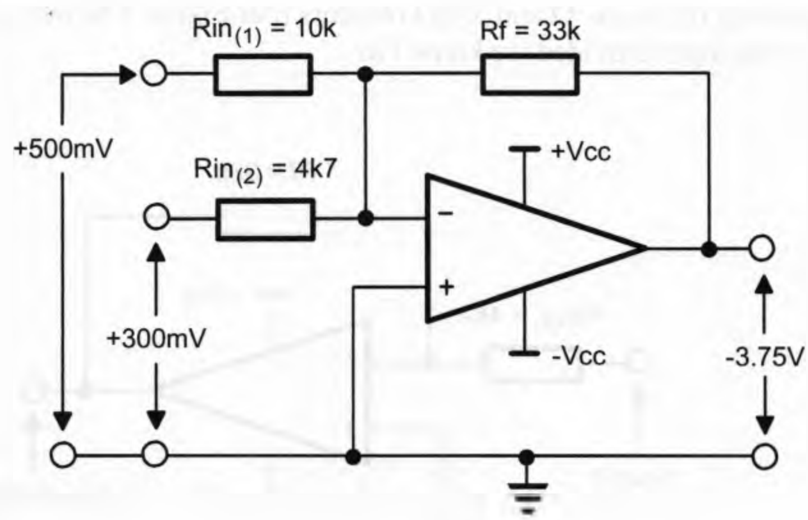


Figure 5 *Applying voltages on both inputs of a summing amp produces a combined effect at the output*

That is, *Vout* due to $Vin_{(1)}$ is -1.65V and *Vout* due to $Vin_{(2)}$ is -2.1V so, the total *Vout* is the sum of the two output voltages and is -3.75V.

It is possible for input voltages of opposite polarities to add in such a way as to partially or fully cancel each other. So, special attention must be paid to using the negative sign in the gain equation when performing the calculations.

Practise finding the output voltage of a summing amp by trying the following questions for yourself.

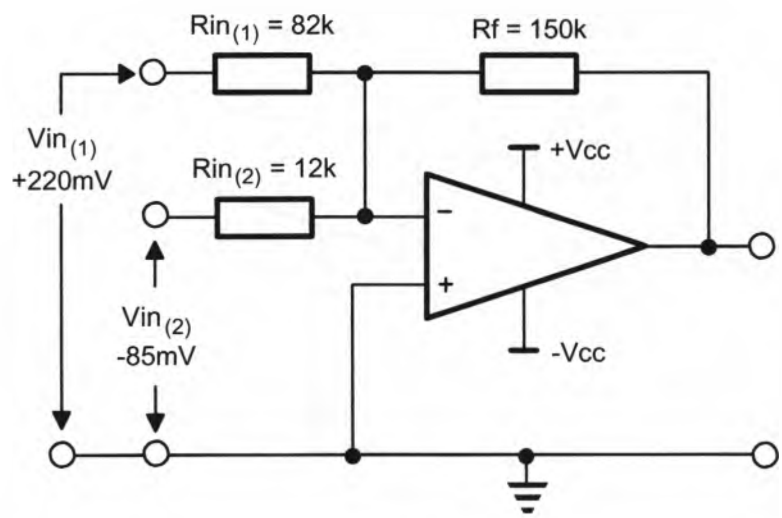


Figure 6

1. What is the output voltage of the summing amplifier in Figure 6?

2. What is the voltage on $Vin_{(2)}$ if $Vin_{(1)}$ remained +220mV but the output is -1.5V?

Summing amps with AC inputs

The summing amplifier's ability to add voltages together can also be used with a combination of DC and AC input voltages and Figure 7 below shows an example of this. With these inputs, the output voltage is an AC signal that is *superimposed* on top of a DC voltage (called a *DC offset*) instead of alternating around zero volts.

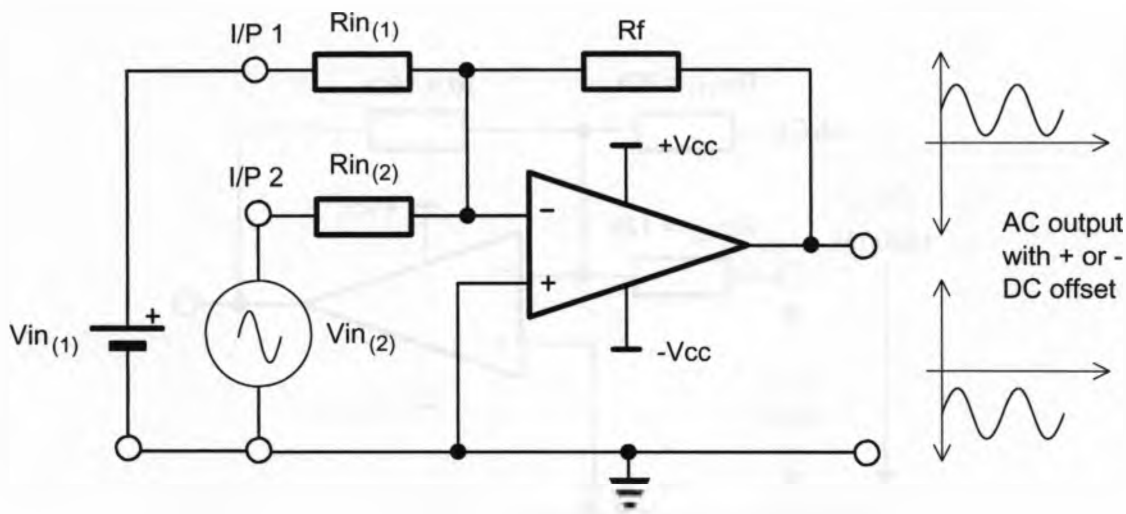


Figure 7 *A summing amp with a combination of DC and AC inputs produces an AC output with a DC offset*

The size of the AC signal and the DC offset can be calculated using the same process that you have just used for the question on the previous page. Let's do an example using the component values from the summing amplifier in Figure 2.

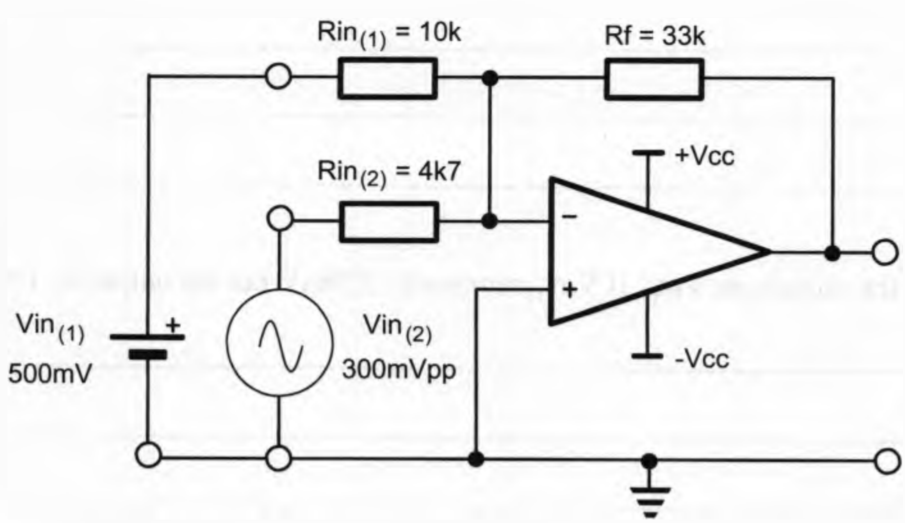


Figure 8 *The circuit in Figure 2 but with the AC and DC inputs shown*

The the input voltages are shown in graph below (Figure 9).

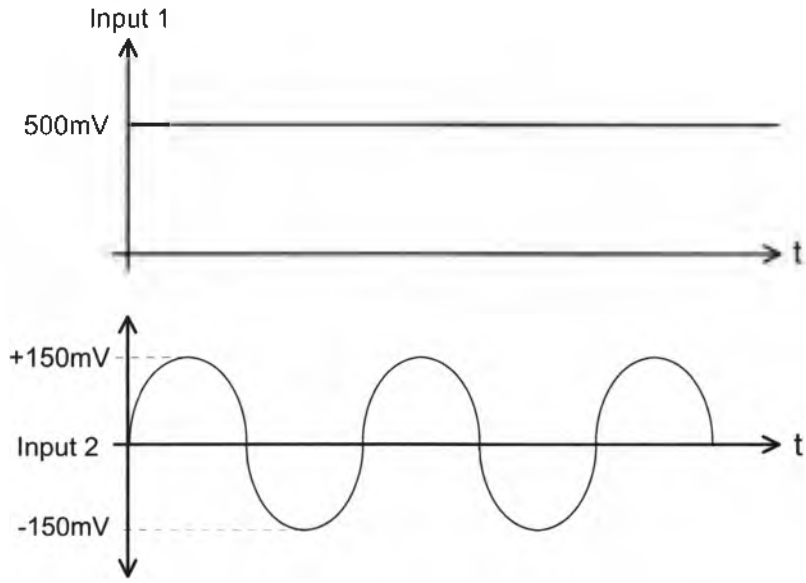


Figure 9 *The inputs to the summing amplifier shown in Figure 7*

The output voltage due to *Input-1* ($Vin_{(1)}$) on its own is $-1.65V_{DC}$ and the output due to *Input-2* ($Vin_{(2)}$) on its own is 2.1Vp-p and phase inverted. So, together, they produce an output as shown in Figure 10 below.

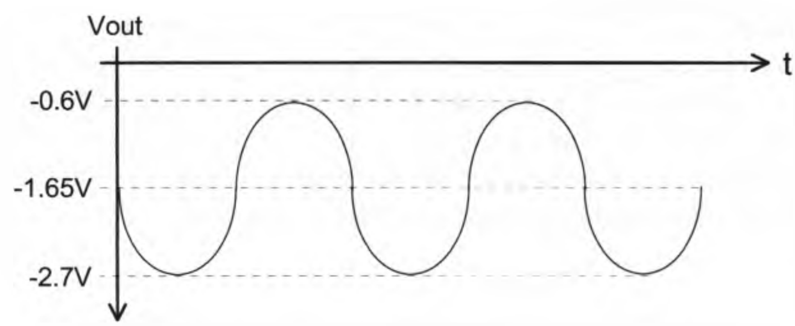


Figure 10 *The output voltage of a summing amp with DC and AC inputs shown in Figure 8*

The summing amplifier can also be used with AC input voltages exclusively (see Figure 11) and this is the basis of an *audio mixer*.

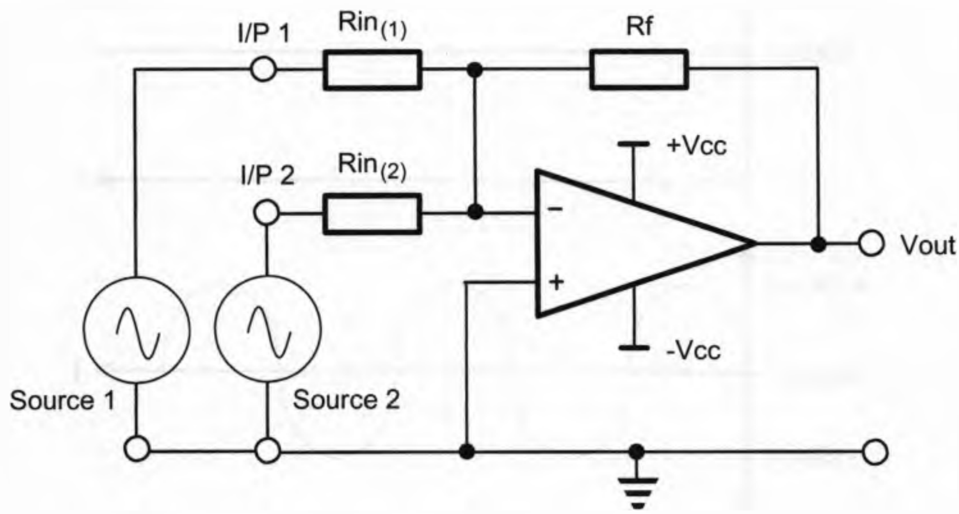


Figure 11 *A summing amp with small signal voltages as inputs*

Determining the output voltage for AC input signals is much more difficult to do than it is with DC input voltages. Although the output will still be the simple addition of the two signals, if the signals are out of phase or their frequencies are different, all sorts of unusual waveforms can be produced at the output. That being the case, you'll not be asked to do this in the theory test.

Applications for summing amps

The summing amplifier can be used in any applications where two or more signals need to be put together to produce one combined signal. As mentioned earlier, this type of amplifier is the basis of an audio mixer or a mixing desk. The input signals to the mixing desk will come from the microphones for the drum kit, guitar, bass, vocals, etc. These signals are combined (mixed) by the summing amps inside the mixing desk and the resultant signal is then power amplified and sent to speakers where the combined effect of all the instruments playing and people singing in the band is heard.

Another very useful application for the summing amplifier is as a Digital to Analogue Converter (DAC). However, we'll leave this for the digital electronics subject.

Troubleshooting inverting op amp configurations

When trying to locate the specific cause of a fault with op amps circuits with negative feedback (like the inverting amplifier), the first thing you must always do is check the power supply rails. Recall that op amps with dual rail supply have both a plus and minus power supply voltage ($\pm Vcc$) that should be the same size. Op amps with a single rail supply have a plus voltage rail ($+Vcc$) and a zero volt rail.

After you've checked the supply rails, the simple test that you can perform on op amps with negative feedback introduced in the last chapter can be used for the inverting and summing amplifiers too. With that said, the measured voltages that you get are not what you might expect. To explain, recall that difference between the two inputs of an op amp circuit with negative feedback is extremely small; so small that it's effectively 0V.

For the inverting and summing amplifiers, the non-inverting input is connected directly to common so its voltage must be 0V with respect common. Given that, and given the difference between the inputs is 0V, it must mean that, if you measure the voltage on the op amp's inverting input with respect to common, it should be 0V as well, regardless of the amp's input voltage. This is shown in Figure 12 with 1V DC connected to an inverting op amp's input. (As an aside, the junction of *Rin*, *Rf* and the op amp's inverting pin is known as *virtual earth* because it's at the same potential s the common rail.)

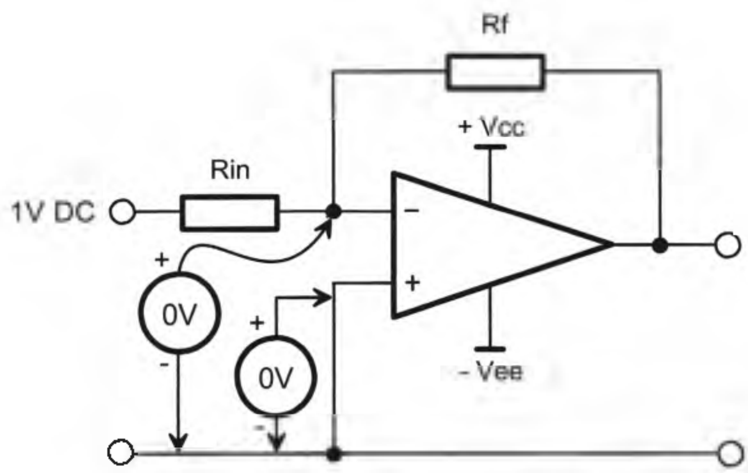


Figure 12 *The voltage on the op amp's two inputs in an inverting amplifier circuit are the same as each other (and are both 0V) because the potential difference between them is approximately 0V*

This will almost certainly feel counter-intuitive to you but it's true. Importantly, knowing this gives us a simple but fabulously useful trick for troubleshooting the inverting and summing amplifiers that you suspect are faulty. Simply measure the op amp's non-inverting and inverting inputs with respect to common as shown in Figure 12.

If the two inputs have exactly the same voltage and are equal to zero volts then this tells you that negative feedback must be operating in the circuit. So this also tells you that the op amp is working and that the feedback resistor (*Rf*) is not open-circuit. In which case, the only possible problems with the circuit are: one of the two resistors has changed value, or *Rin* has gone open-circuit, or there's no input signal (perhaps due to a cracked PCB track or dry-joint).

However, if the op amp's inverting input is not exactly 0V then this tells you that negative feedback is not operating in the circuit. In which case, possible problems include: the op amp may be faulty, or the feedback resistor is open-circuit, or the loop is broken for some other reason (perhaps due to a cracked PCB track or dry-joint).

Words that may be new to you

Inverting amplifier A closed-loop op amp configuration where the output voltage is always phase inverted.

Virtual earth A point on the inverting op amp configuration where the voltage is so low that it is said to be at earth potential. This term harks back to the days when the common was always connected to earth. As that's seldom the case these days, then perhaps a better term would be "virtual common".

Student notes

Skill practice 7

Practise measuring the voltage gain and bandwidth of amplifier circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you approximately 1½ hours to complete this exercise.

Equipment

- Emona Trainer (or a prototyping breadboard)
- DMM
- TL071 op amp
- 10kΩ ¼W resistor
- 18kΩ ¼W resistor
- 33kΩ ¼W resistor
- 68kΩ ¼W resistor
- 560kΩ ¼W resistor
- three BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ____________________ ____________________ ____________________	Move bags and other objects from walkways Plan lifting of equipment Other: ____________________ ____________________ ____________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ____________________ Date: ____________________

Part A - The inverting amplifier

2. Gather the equipment needed for this exercise.

3. Connect the circuit in Figure 1 on the Emona trainer.

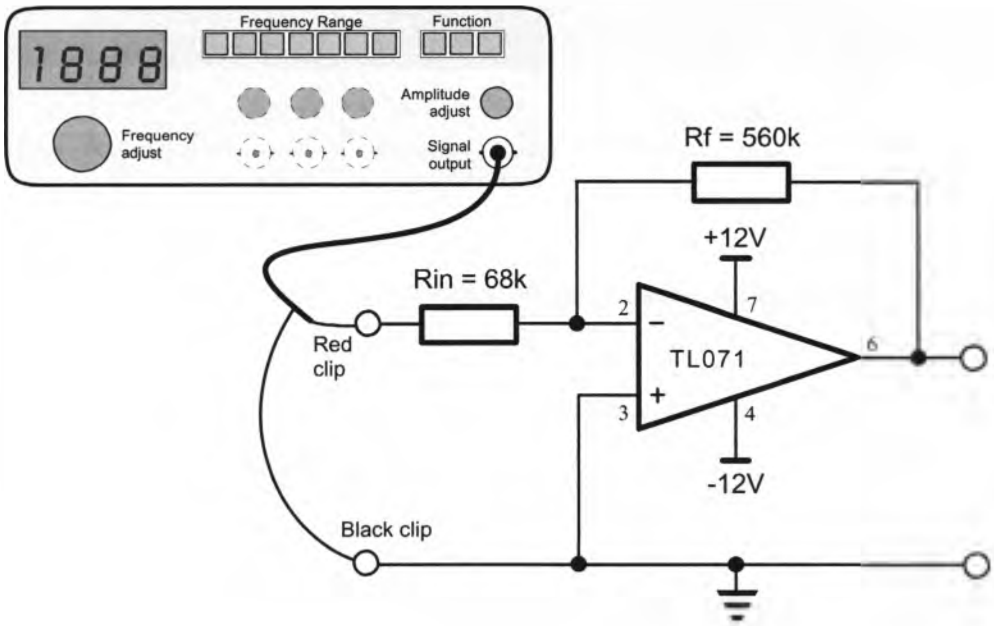


Figure 1

4. Calculate the amplifier's theoretical voltage gain using the equation $Av = -(\frac{Rf}{Rin})$. Record your answer in Table 1 on the next page.

5. Calculate and record the amplifier's theoretical output for a 500mVpp AC input.

6. Connect the CRO's channel 1 input to the amplifier's input.

7. Adjust the amplifier's input signal for a 500mVpp 1kHz sinewave.

8. Connect the CRO's channel 2 input to the amplifier's output and adjust the CRO to observe both the input and output signals at the same time.

9. Check that the output voltage is not clipping.

   Note: If it is, reduce the input voltage and record the new *Vin* in Table 1.

10. Measure and record the amplifier's output voltage.

11. Calculate and record the actual gain of the amplifier using the equation $Av = \frac{Vout}{Vin}$ and your measured values of Vin and $Vout$.

Table 1

Theoretical Av (Step 4)	**Vin**	**Theoretical Vout** (Step 5)	**Measured Vout** (Step 10)	**Actual Av** (Step 11)
	500mVpp			

Question 1
How do the theoretical and measured voltage gains compare? What might explain any differences?

____

____

Question 2
What is the phase relationship between the input and the output?

____

12. Simulate a fault condition where the feedback resistor has gone open-circuit by removing it from the circuit.

13. Briefly describe what happened to the output voltage.

____

____

Question 3
Why did removing the feedback resistor have the effect that you observed?

____

____

The teacher needs to check your work at this point...

Part B - The Summing Amplifier

14. Connect the circuit of Figure 2 on the Emona Trainer but don't turn it on.

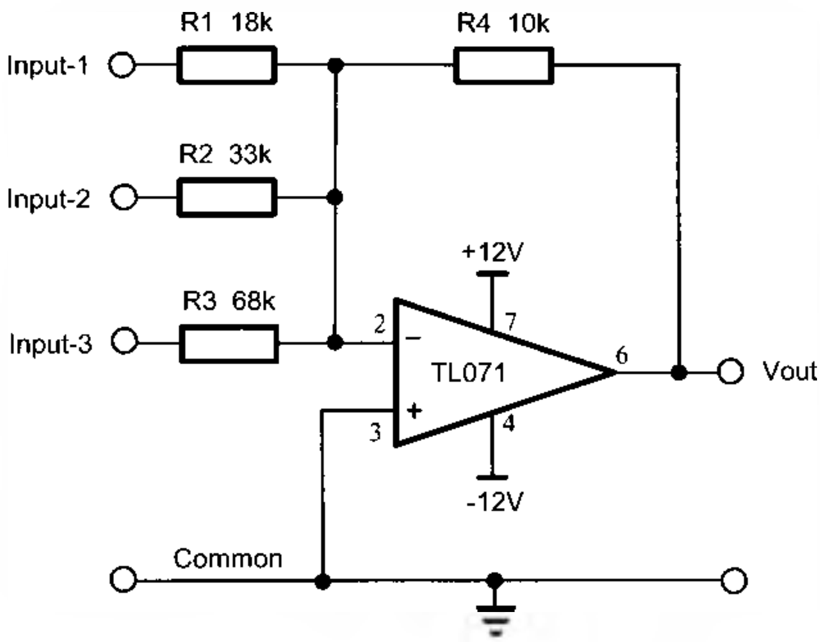


Figure 2

15. Calculate the theoretical gain for each stage. Record the values in Table 2 below.

    Note: Each input has been set-up for a gain of less than one. In other words, each input will attenuate the signal on the input rather than amplifier it! This has been done to avoid overdriving the amplifier.

Table 2	Input-1	Input-2	Input-3
Calculated Gain			

16. Turn on the Emona Trainer.

17. Connect Inputs 2 and 3 to common.

18. Set up one of the bench-mounted DC power supply's outputs for 10V DC.

19. Connect the DC power supply's positive terminal to the amplifier's *Input-1* and its negative terminal to the amplifier's common.

20. Measure the circuit's output voltage using the DMM noting polarity. Record this information the Table 3 below.

21. Calculate and record the gain for *Input-1* using the equation: $Av_{(1)} = \frac{Vout}{Vin_{(1)}}$.

22. Disconnect the DC power supply from *Input-1* then connect *Input-1* to common.

23. Disconnect *Input-2* from common and connected the DC power supply to *Input-2*.

24. Measure and record the circuit's new output voltage noting polarity.

25. Calculate and record the gain for *Input-2* using the equation: $Av_{(2)} = \frac{Vout}{Vin_{(2)}}$.

26. Disconnect the DC power supply from *Input-2* then connect *Input-2* to common.

27. Disconnect *Input-3* from common and connected the DC power supply to *Input-3*.

28. Measure and record the circuit's new output voltage noting polarity.

29. Calculate and record the gain for *Input-3* using the equation: $Av_{(3)} = \frac{Vout}{Vin_{(3)}}$.

Table 3

Input	Output	Gain
Input-1 = +10V		
Input-2 = +10V		
Input-3 = +10V		

Question 4

Compare the calculated gain values in Table 2 with the measured gain values in Table 3. What might explain any differences?

Question 5

What type of amplifier configuration would the circuit be if it only had one of its inputs?

The teacher needs to check your work at this point...

30. Disconnect all three inputs from common and connect them to the DC power supply.

31. Measure the circuit's new output voltage noting polarity. Record this measurement in Table 4 below.

Table 4

Vout with +10V on all three inputs	

Question 6

What is the relationship between the output voltage with all three inputs connected to 10V and the output voltage when each input is connected to 10V on its own?

The teacher needs to check your work at this point...

32. Leave the DC power supply connected to *Input-1*.

33. Disconnect *Input-3* from the DC power supply and connect it to common.

34. Adjust the function generator to output a 5Vpp sinewave at 1kHz.

35. Disconnect *Input-2* from the DC power supply and connect it to the function generator.

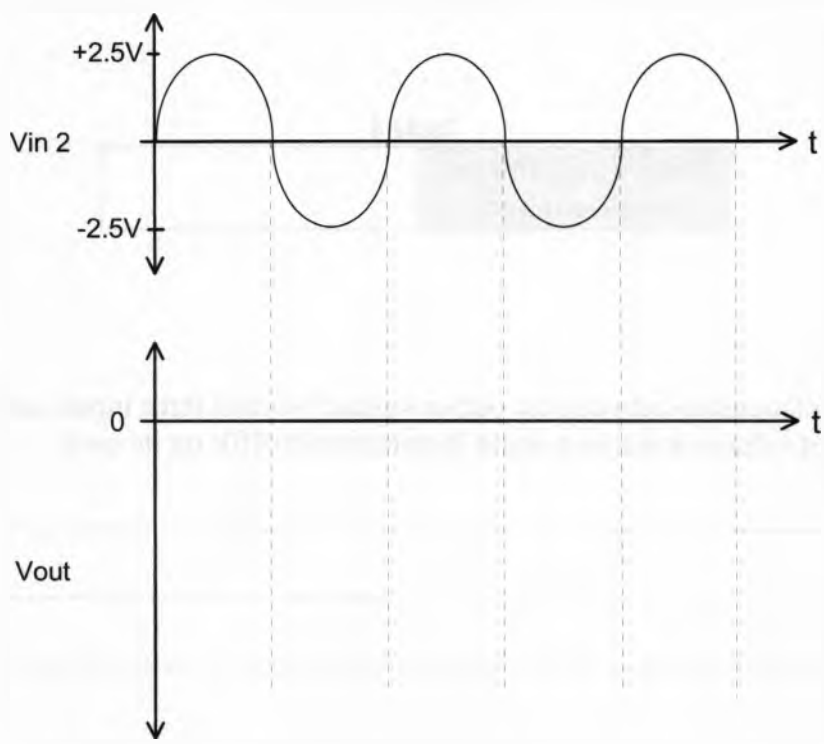
36. Connect the CRO's channel 1 input to *Input-2*.

37. Connect the CRO's channel 2 input to the amplifier's output.

38. Set the channel 2 *Vertical Attenuation* control to 1V/div.

39. Set the channel 2 *Input Coupling* control to DC.

40. On the diagram below, sketch the waveform that you observed at the output. Make sure you clearly show the DC offset of the signal and all voltage and time information.



Question 7
Why does the output voltage contain a DC offset? (Note: Call the teacher if it doesn't).

Question 8
Why is the DC offset the opposite polarity to the DC voltage on *Input-1*?

Question 9
Why is the AC output signal phase inverted when compared with the AC signal on *Input-2*?

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 12 refer to Figure 1

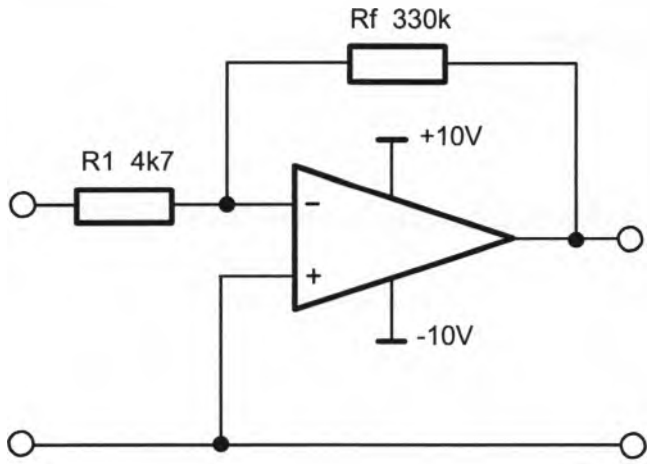


Figure 1

1. What type of closed-loop op amp configuration is this circuit?

2. Calculate the circuit's voltage gain.

3. What is the phase relationship between input and output?

4. What is the maximum peak-to-peak output voltage before clipping would occur?

5. Calculate the maximum input voltage before clipping would occur at the output.

6. What is the input resistance?

7. Calculate the circuit's bandwidth if the op amp's GBWP is 1MHz.

8. Calculate the circuit's input voltage if its output voltage is 5Vp-p.

9. What is the voltage on the op amp's inverting input if the circuit's input voltage is 2Vpp?

10. What two separate changes could be made to make the gain -10?

11. Which change would be the best one to make? Explain your answer.

12. Calculate the circuit's new bandwidth with a gain of -10.

For the following fault-finding questions, assume in each case that the power supply has been checked and found to be ok.

13. Figure 2 below shows a faulty inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty.

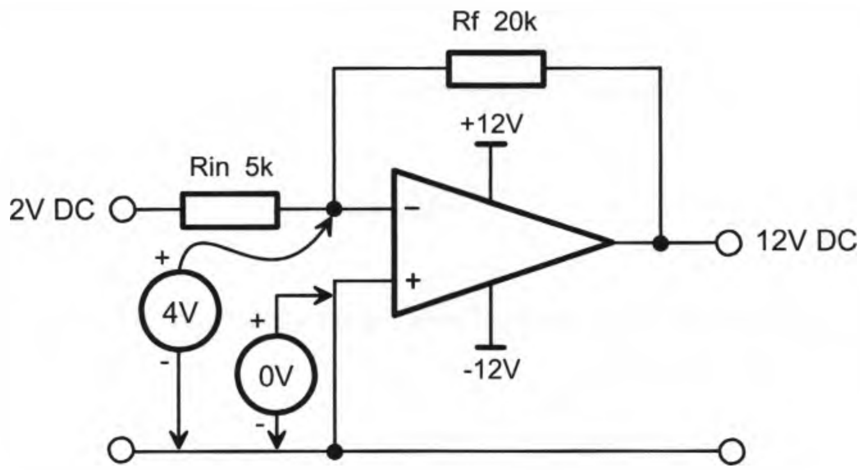


Figure 2

14. Justify your answer to Q13 in terms of how the measurements in the circuit support your conclusion.

15. Figure 3 below shows a faulty inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty and what's wrong with it.

___

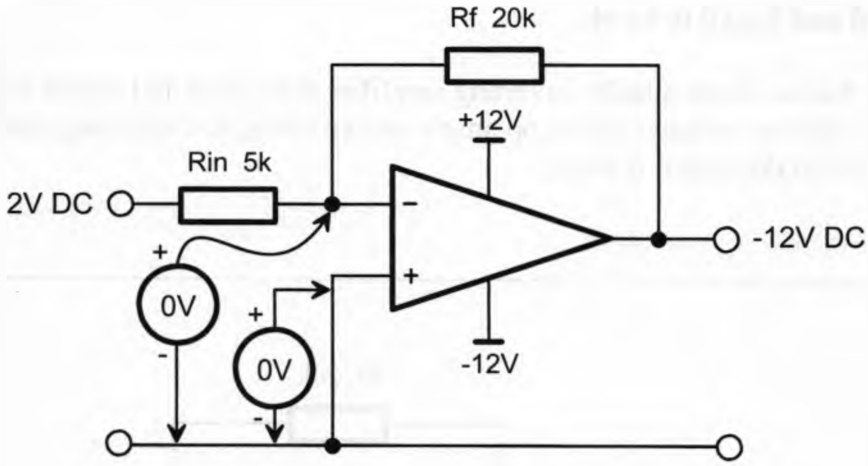


Figure 3

16. Justify your answer to Q15 in terms of how the measurements in the circuit support your conclusion.

___

___

___

___

17. Figure 4 below shows a faulty inverting amplifier with input and output voltages shown together with the voltages on the op amp's non-inverting and inverting pins. State what component in the circuit is faulty and what's wrong with it.

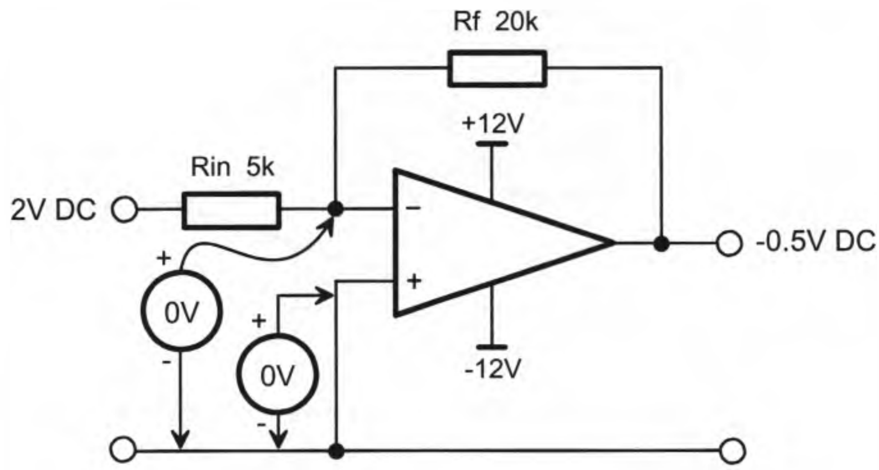


Figure 4

18. Justify your answer to Q17 in terms of how the measurements in the circuit support your conclusion.

Questions 19 to 27 refer to the circuit of Figure 5

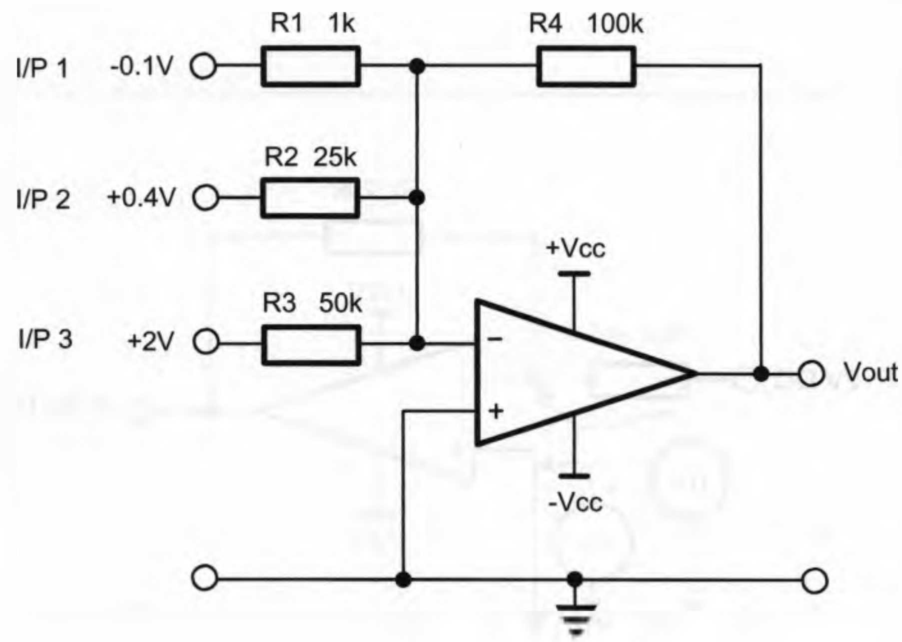


Figure 5

19. What type of closed-loop op amp configuration is this circuit?

____

20. Calculate the gain for each input in the circuit.

____

____

____

____

____

____

21. Calculate the output voltage that would be produced by each individual input voltage given the input voltages shown.

22. Calculate the output voltage that would be produced when all three input voltages are applied to the circuit at the same time.

23. For the input voltages shown, what is the voltage on the op amp's inverting input?

24. State the input resistance that would be "seen" by the source connected to each input.

25. With all three input voltages applied, what would be the effect on the output voltage for this circuit if resistor *R1* became open? Explain why.

26. With all three input voltages applied, what would be the effect on the output voltage for this circuit if resistor *R4* became open?

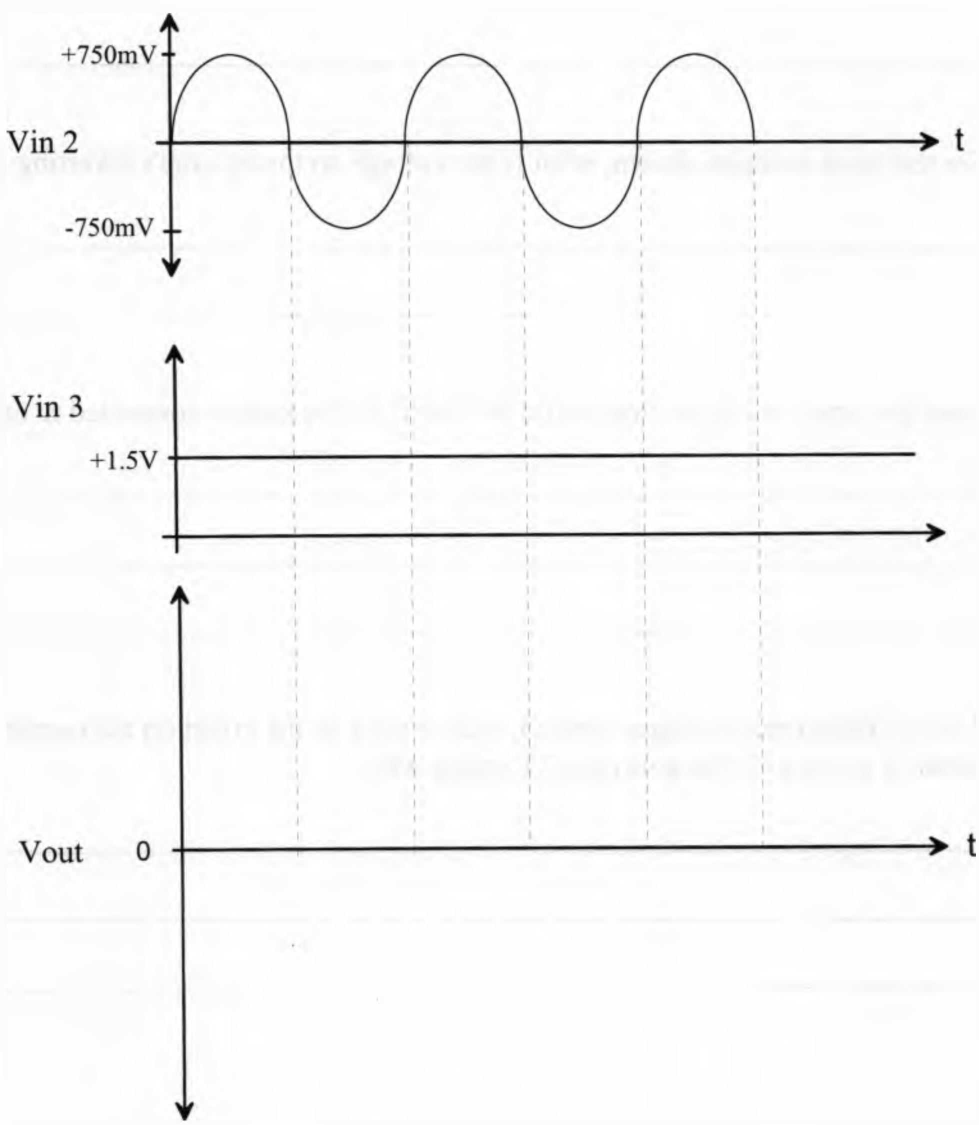
____

____

____

27. For the input voltages indicated below, draw the waveform that you would expect to see at the output of the summing amp.

Vin 1 connected to ground (in other words, 0 volts)



Section 8 The differencing amplifier

Purpose

To develop your ability to predict the output voltage of the differencing amplifier given the input conditions.

Objectives

Once you have completed this section you should be able to:

- Recognise the differencing amplifier op amp configuration in a schematic diagram
- Predict the type, magnitude and phase of the output voltage for the differencing amplifier given a set of input conditions
- Give applications for the differencing amplifier
- Give reasons for why faulty op amps may sometimes need to be replaced by a suitable substitute instead of the original part.
- Choose a suitable replacement op amp using a table of manufacturers' data basing your decision on the following op amp parameters: power supply requirements; GBWP; frequency compensation; and pinout.
- Verify the operation of the differencing amplifier

Introduction

So far we have considered four closed-loop op amp configurations: these being the non-inverting amplifier, the voltage follower, the inverting amplifier the summing amplifier. In this section we consider the last closed-loop op amp configuration for this unit; the Differencing Amplifier. [This circuit is also often called the *differential amplifier* but name isn't used here to avoid confusion with the discrete component differential amplifier that you'll learn about for an other unit.]

The differencing amplifier

Recall that in Section 5 we found that an op amp operating in the open-loop mode amplifies the difference between the two inputs by the op amp's open-loop gain. The output voltage of an open-loop op amp is found by using the equation: $Vout = (Vin_{non-inverting} - Vin_{inverting}) \times Av_{OL}$.

The problem with operating the op amp in open-loop mode is that it's unusable as a practical amplifier because the open-loop gain is so high and so it's impossible not to overdrive the amplifier. Negative feedback is introduced to reduce the voltage gain but doing so when implementing the non-inverting and inverting amplifiers reduces the number of the circuits' inputs to one.

The differencing amplifier has negative feedback too but it has two inputs and not one. It operates in a similar way to the open-loop op amp in that it amplifies the difference between the two inputs but does so using the circuit's closed-loop voltage gain instead of its open-loop voltage gain. The circuit is shown in Figure 1 below.

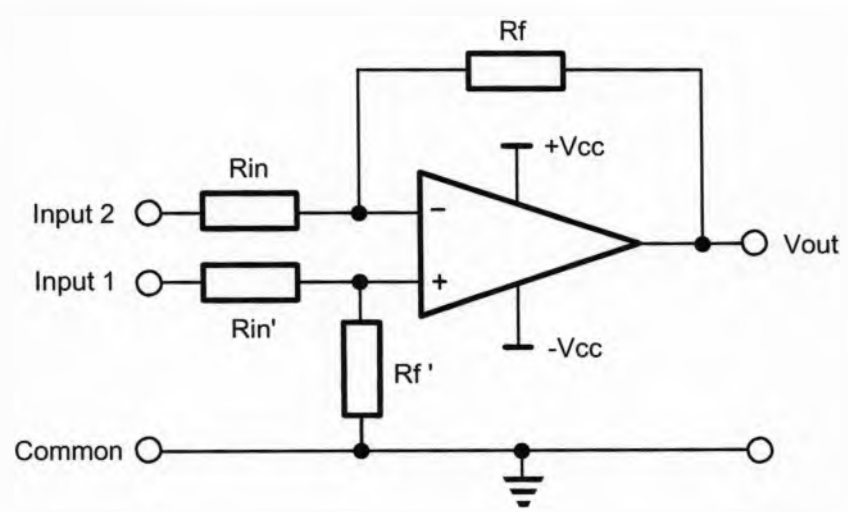


Figure 1 *The differencing amplifier*

The equation for finding the output voltage of the differencing amplifier is:

$$Vout = (Vin_{(1)} - Vin_{(2)}) \times Av_{CL}$$

And the equation for finding the closed-loop voltage gain is:

$$Av_{CL} = \frac{Rf}{Rin}$$

Combining these two equations gives us a general equation for finding the output voltage:

$$\boxed{Vout = (Vin_{(1)} - Vin_{(2)}) \times \frac{Rf}{Rin}}$$

Where:
Rf = Rf ' and
Rin = Rin'

Let's do an example. What is the output voltage of the differencing amplifier in Figure 2 below?

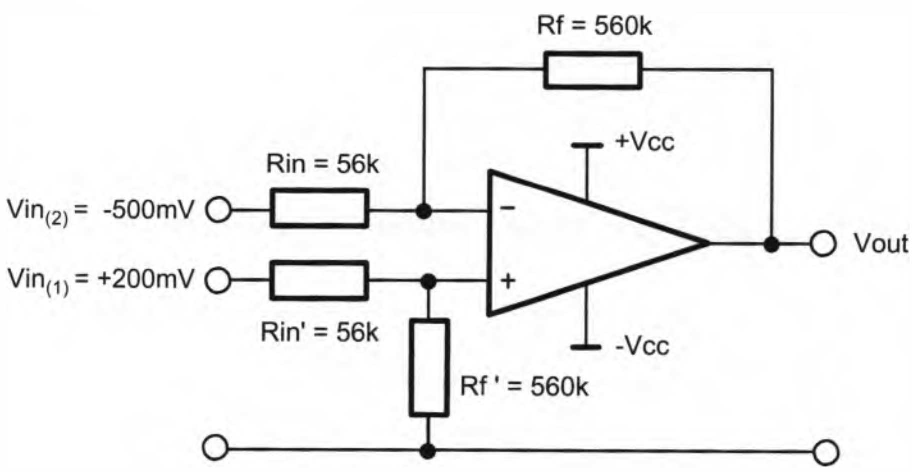


Figure 2

$$Vout = (Vin_{(1)} - Vin_{(2)}) \times \frac{Rf}{Rin}$$

$$Vout = (200\text{mV - -}500\text{mV}) \times \frac{560k}{56k}$$

$$Vout = 700\text{mV} \times 10$$

$$Vout = 7\text{V}$$

Practise using the equation by trying the following questions for yourself.

1. What is the output voltage of a the differencing amplifier in Figure 3 if $Vin_{(1)}$ = +900mV DC and $Vin_{(2)}$ = +1.3V DC?

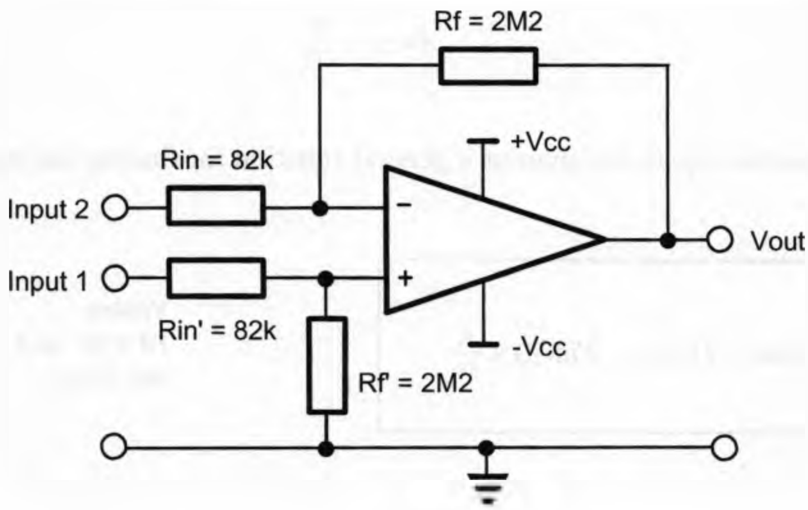


Figure 3

2. What must $Vin_{(1)}$ in Figure 3 have changed to if *Vout* changed to +6V?

3. What is the output voltage of a the differencing amplifier in Figure 3 if both $Vin_{(1)}$ and $Vin_{(2)}$ = -320mV DC?

Notice that the differencing amplifier produces 0V at the output when the input voltages are the same as each other. This is a very handy feature of the differencing amplifier and is one of the main reasons for using it, as you will see.

The differential amplifier's ability to amplify the difference between two input voltages can be used with AC voltages as well as DC voltages and Figures 4 and 5 show examples.

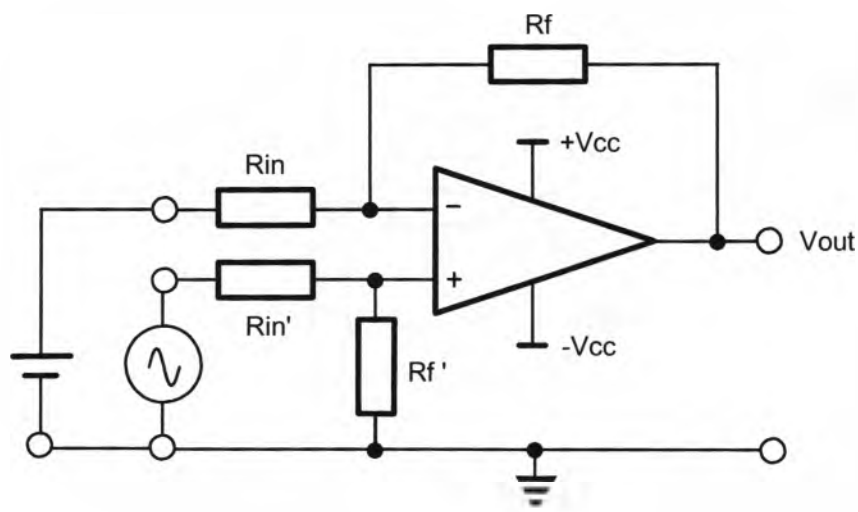


Figure 4 *A differential amplifier with a DC input signal and an AC input signal*

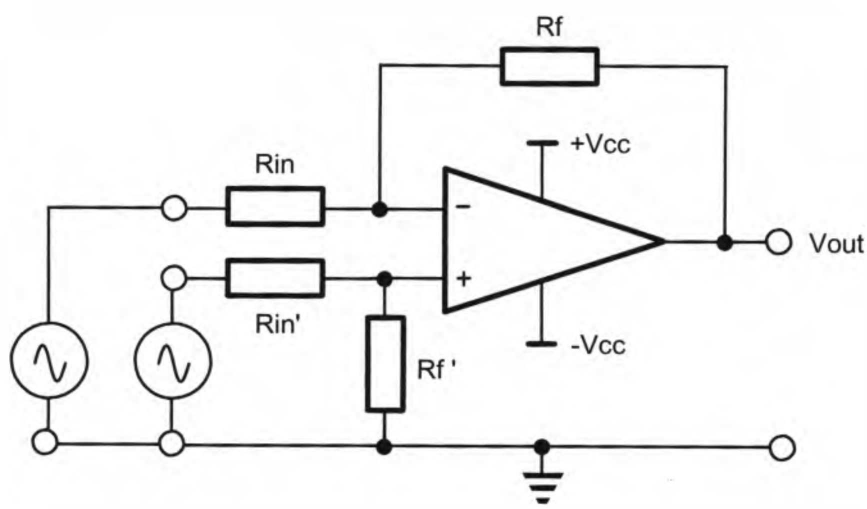


Figure 5 *A differential amplifier with two AC input signals*

Applications for the differencing amplifier

The most common application for a differencing amplifier is in systems requiring noise rejection. Figure 6 below shows an example using a balanced-output microphone (the type widely used in pro-audio applications).

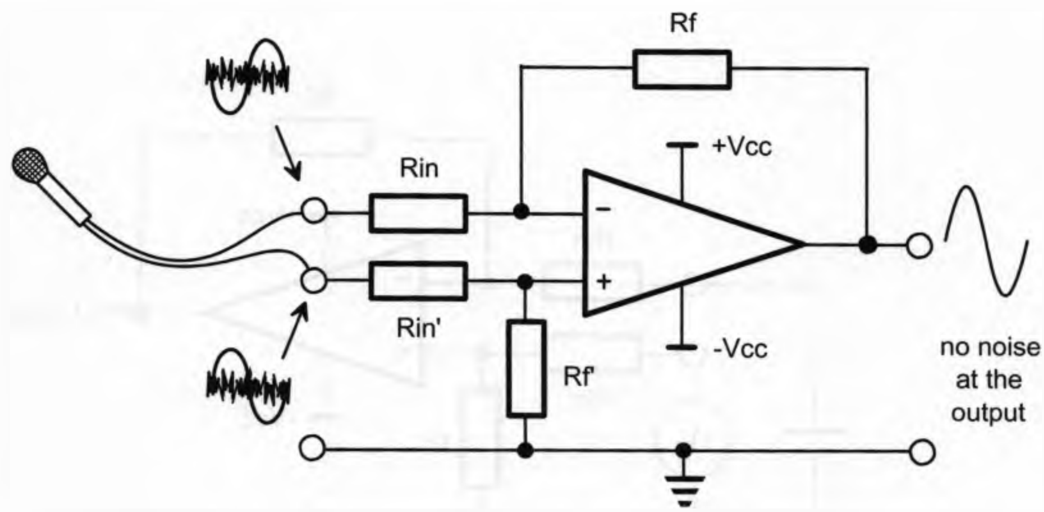


Figure 6 *A differencing amplifier used in a telecommunications application*

With a balanced system, both conductors carry a copy of the signal but they're phase-inverted with respect to each other (as shown in Figure 6). As the microphone's conductors are likely to be long (they've got to travel from the stage back to the mixing desk), they're likely to pick up a noticeable amount of electrical noise (even if the cables are shielded!). Importantly, the noise signal is identical on both conductors and in-phase with one another. As the differencing amplifier only amplifies the difference between its inputs, the desired signal is amplified but the noise is not. This cancelling of common signals is known as *common mode rejection.*

Choosing suitable substitutes when replacing faulty op amps

Ordinarily, when a component in a circuit fails and needs replacing, you would do so with exactly the same part. However, there are times when you have to replace a faulty part with a substitute that is a close match to the original (so, in other words, a "best fit" device). That can happen when the repair is urgent and the replacement device is not readily available. Or, when the equipment is older and the original part is no-longer available.

When choosing a substitute device for a faulty op amp, the replacement must have the same power supply requirements as the original and a gain bandwidth product (GBWP or UGBP) close to, or above, that of the original. And, if the original part has internal *frequency compensation*, the replacement must have it too. (Knowledge of exactly what *frequency compensation* is, is beyond the requirements of this Unit.) Ideally, the two devices would also have the same pin-out, otherwise some modification of the circuit board would be needed which is best avoided unless absolutely necessary.

With that said, choosing a substitute invariably requires some knowledge of other op amp performance parameters beyond the requirements of this unit. This include knowledge of:

- power dissipation
- slew rate
- common mode rejection ratio (CMRR)
- input bias currents
- input offset voltages and currents

Any assessment questions related to choosing suitable substitutes for op amps will only ask you to consider power supply requirements, GBWP, frequency compensation and pinout. Table 1 below is provided to show you the variety of specifications there are for several of these parameters among commonly available op amps.

Table 1

Type	Device	UGBP (MHz)	Slew Rate (V/µS)	Supply voltage		CMRR (dB)	Internal Freq. Comp.
				Min	Max		
AD8506	Low current input	95k	13m	±0.9V	±2.5V	105	Yes
LM301	GP Amp	1	0.5	±3V	±18V	70	No
LM741	GP Amp	1	0.5	±3V	±18V	70	Yes
LTC2057	Low drift	1.5	0.45	±4.75V	±36V	150	Yes
NE5534	Low noise	10	6	±3V	±22V	70	No
MAX9943	Precision	2.4	0.35	+6V	+38V	125	Yes
TL071	JFET low noise	3	13	±3.6V	±18V	70	Yes
MC3317	Low power	1.8	2.1	±1.5V	±22V	90	Yes
CA3130	MOSFET input	4	10	±2.5V	±8V	70	No
CA3140	MOSFET input	4.5	9	±2V	±18V	70	Yes
LM10C	Inc. voltage ref.	0.1	*	+1.1V	+45V	87	Yes

Use the information in Table 1 on the previous page to answer the following questions.

1. Which device(s) would be a suitable substitute(s) for a faulty LM741 op amp operated in a circuit from ±14V supply rails?

2. Why might a CA3130 not be a suitable substitute for the a faulty LM301 operated of ±5V supply rails?

3. Why can't the CA3140 be used to replace a faulty MAX9943 operated of a 9V supply rail?

Skill practice 8

Practise measuring the voltage gain of amplifier circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you approximately 1½ hours to complete this exercise.

Equipment

- Emona Trainer (or a prototyping breadboard)
- DMM
- LM741 op amp
- 27Ω ¼W resistor
- 100Ω ¼W resistor
- 470Ω ¼W resistor
- 1k2Ω ¼W resistor
- two 10kΩ ¼W resistors
- two 82kΩ ¼W resistors
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ______________________ ______________________ ______________________	Move bags and other objects from walkways Plan lifting of equipment Other: ______________________ ______________________ ______________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ______________________ Date: ______________

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the Emona Trainer. When you do, also connect the bench-mounted DC power supply's negative terminal to the trainer's ground terminal.

   Note: Don't dismantle this circuit at Step 4 because you're going to connect the two circuit's together.

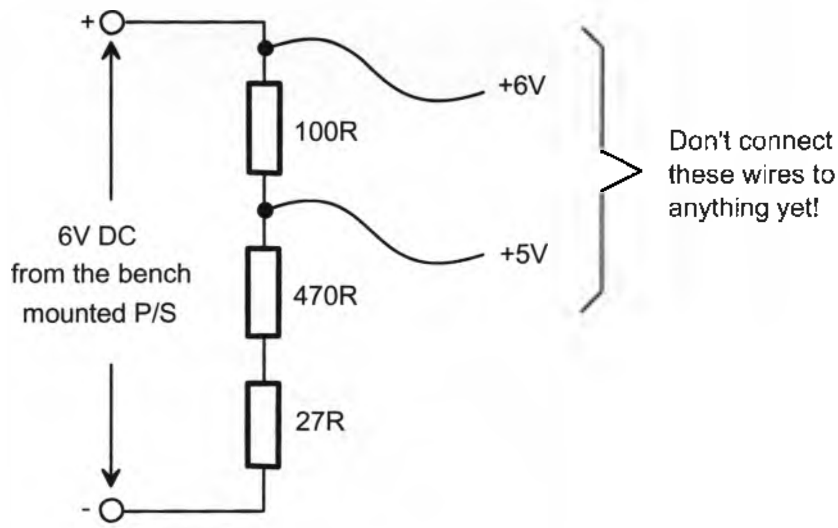


Figure 1

4. Connect the circuit of Figure 2 on the Emona Trainer.

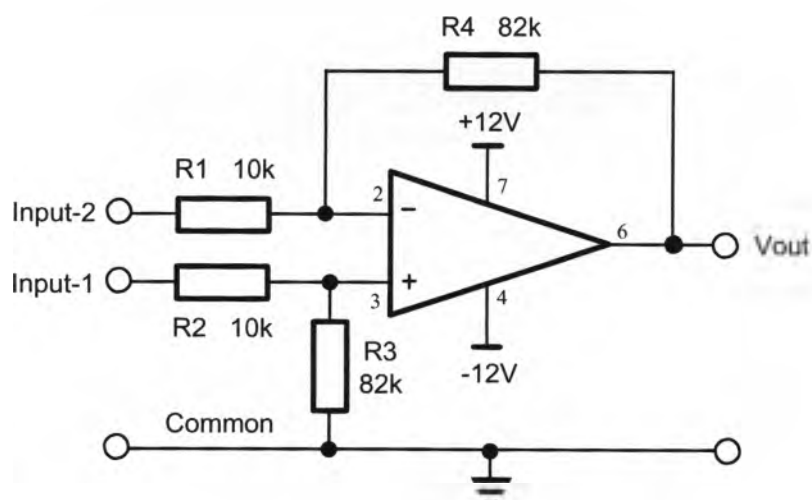


Figure 2

5. Calculate the output voltage if $Vin_{(1)}$ = +5V and $Vin_{(2)}$ = +6V. Record your answer in Table 1 below.

6. Using the voltage divider circuit that you wired in Step 3, connect +5V to Input-1 and +6V to Input-2 of the differencing amplifier.

7. Measure and record the output voltage.

Table 1

Theoretical Vout (Step 5)	Measured Vout (Step 7)

The teacher needs to check your work at this point...

8. Calculate the output voltage if $Vin_{(1)}$ = +6V and $Vin_{(2)}$ = +5V. Record this value in Table 2.

9. Connect +6V to Input-1 and +5V to Input-2

10. Measure and record the output voltage.

Table 2

Theoretical Vout	Measured Vout

11. Calculate the output voltage if +5V were applied to both inputs. Record this value in Table 3.
12. Connect +5V to both inputs.
13. Measure and record the output voltage.

Table 3

Theoretical Vout	Measured Vout

Question 1
What was the potential difference between the two inputs of the differencing amplifier in Step 6? By how much did the amplifier amplify this potential difference?

____

____

Question 2
Why did the polarity of the measured output voltage reverse between Steps 7 and 10?

____

____

Question 3
Why was the output almost zero volts in Step 12?

____

____

Question 4
What changes would be necessary if you wanted to halve the gain of the differential amplifier?

____

____

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 4 refer to the circuit in Figure 1

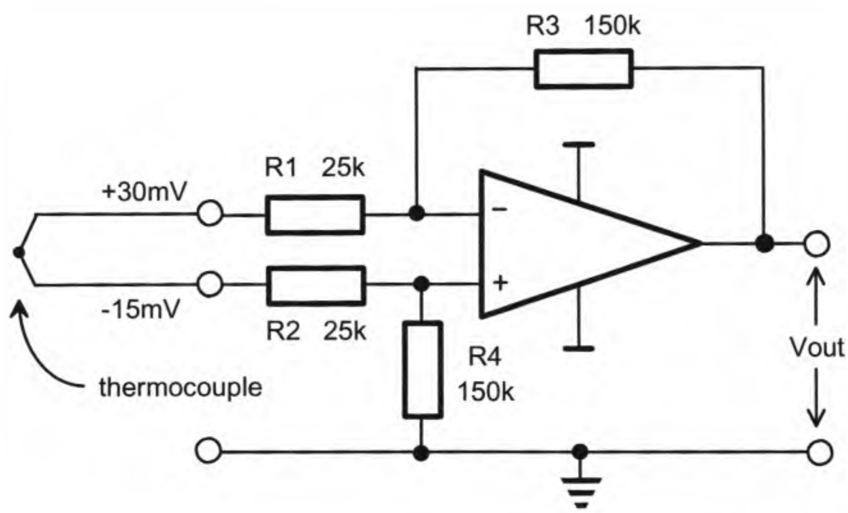


Figure 1

1. What is the closed-loop voltage gain?

2. Calculate the output voltage for the input voltages given.

3. What is the potential difference between the inverting and non-inverting pins on the op amp?

4. What changes could be made to double the voltage gain of this circuit?

Student notes

Appendix 1

Section summaries

The theory notes in each Section of this workbook are designed to help you learn about amplifier fundamentals. But when you think about it, there's a difference between learning and remembering. These section summaries are designed to help you remember the theory.

Section 1

Objectives and Summary

1. Explain the purpose of small signal amplifiers and where they are used

   Small signal amplifiers increase the size of a signal's voltage, current or power. Typical input voltages of small signal amps range from 10mV to 500mV and typical output voltages range from 100mV to 10V. They are used in most analog circuits.

2. Calculate the voltage/current/power gain of an amplifier (as a ratio)

   Use the review questions to practise this. The equations are:

   Voltage gain: $Av = \frac{Vout}{Vin}$

   Current gain: $Ai = \frac{Iout}{Iin}$

   Power gain: $Ap = \frac{Pout}{Pin}$

3. Determine either the input or output voltage/current/power of an amplifier given its gain (as a ratio) and the output or input voltage/current/power

   Use the review questions to practise this. The equations are:

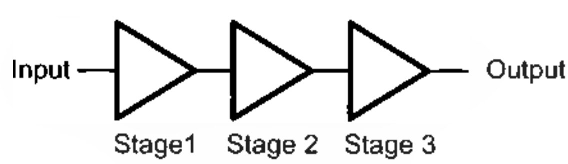
   Transposing $Av = \frac{Vout}{Vin}$ gives: $Vin = \frac{Vout}{Av}$ and $Vout = Av \times Vin$

   Transposing $Ai = \frac{Iout}{Iin}$ gives: $Iin = \frac{Iout}{Ai}$ and $Iout = Ai \times Iin$

   Transposing $Ap = \frac{Pout}{Pin}$ gives: $Pin = \frac{Pout}{Ap}$ and $Pout = Ap \times Pin$

4. Calculate the total gain of a cascaded amplifier (as a ratio)

   An example of a 3 stage cascaded amplifier is shown on the right.

   When the individual stage gains are expressed in ratios, the total gain as a ratio is found using the equation:

   $Av_{(T)} = Av_{(1)} \times Av_{(2)} \times Av_{(3)}$

5. Explain the term *input/output phase relationship*

   This is the phase relationship between an amplifier's input and output signals. The input and output signals are usually either in phase or phase inverted (though other phase relationships are possible but they're not discussed in this module).

6. Explain the term *distortion*

   Distortion is a change in shape of an amplifier's output signal compared to its input (and is usually undesirable though there are exceptions).

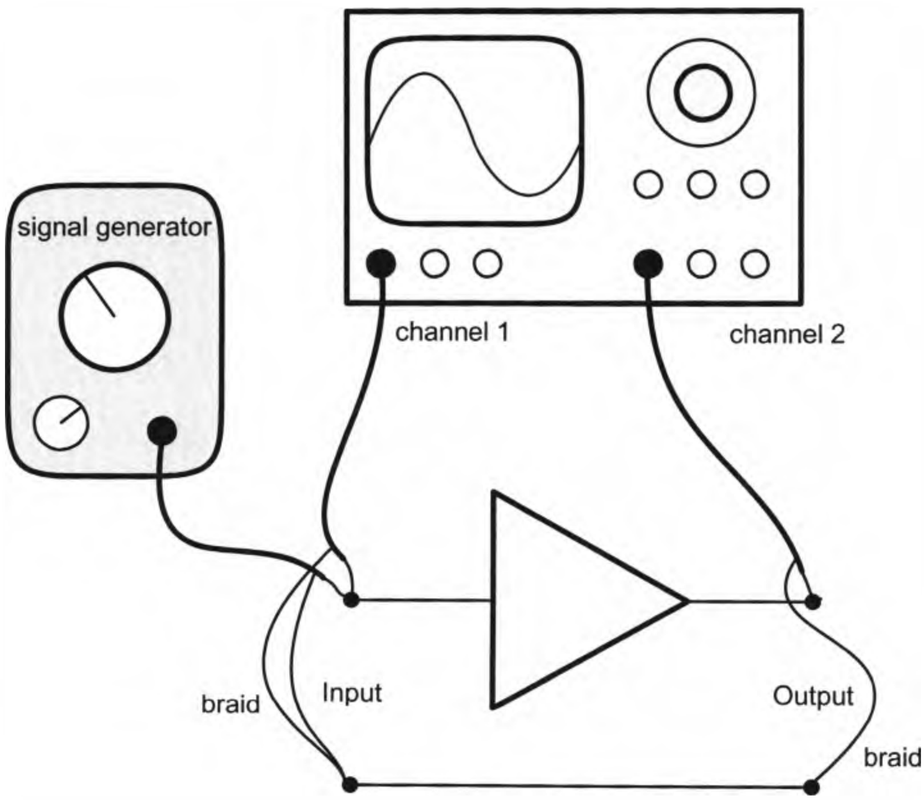
7. Explain what *overdriving* an amplifier means and the effect on the amplifier's output signal

   Overdriving an amplifier occurs when the input signal too big for the amplifier's gain or the amplifier's gain too big for the input signal. It wants to cause the amplifier's output voltage to be bigger than the power supply voltage which is impossible.

   If the input to an overdriven amplifier is a signal like a sinewave or a triangular wave, you would see a *clipped* version of the waveform on the amplifier's output. You would not see clipping on a squarewave.

8. Measure the voltage gain of an amplifier

To measure gain, use the set-up shown below to apply an input signal to an amplifier. Next, check that the output signal is not clipped. If it is, reduce the amplitude of the input signal. Measure the amplitude of the input and output signals then use the equation $Av = \frac{Vout}{Vin}$ to calculate the gain (as a ratio).



Section 2

Objectives and Summary

1. Calculate the voltage/current/power gain of an amplifier in decibels

   Use the review questions to practise this. The equations are:

   Voltage gain: $Av_{(dB)} = 20Log\frac{Vout}{Vin}$

   Current gain: $Ai_{(dB)} = 20Log\frac{Iout}{Iin}$

   Power gain: $Ap_{(dB)} = 10Log\frac{Pout}{Pin}$

2. Determine either the input or output voltage/current/power of an amplifier given its gain as a decibel and the output or input voltage/current/power.

   Use the review questions to practise this. The equations are:

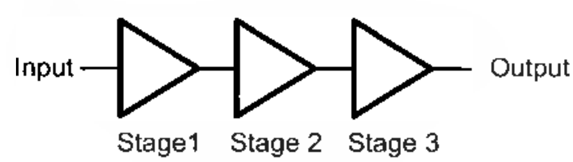
   Transposing $Av_{(dB)} = 20Log\frac{Vout}{Vin}$ gives: $Vin = \frac{Vout}{Log^{-1}\left(\frac{Av_{(dB)}}{20}\right)}$ and $Vout = Vin\left[Log^{-1}\left(\frac{Av_{(dB)}}{20}\right)\right]$

   Transposing $Ai_{(dB)} = 20Log\frac{Iout}{Iin}$ gives: $Iin = \frac{Iout}{Log^{-1}\left(\frac{Ai_{(dB)}}{20}\right)}$ and $Iout = Iin\left[Log^{-1}\left(\frac{Ai_{(dB)}}{20}\right)\right]$

   Transposing $Ap_{(dB)} = 10Log\frac{Pout}{Pin}$ gives: $Pin = \frac{Pout}{Log^{-1}\left(\frac{Ap_{(dB)}}{10}\right)}$ and $Pout = Pin\left[Log^{-1}\left(\frac{Ap_{(dB)}}{10}\right)\right]$

3. Calculate the total gain of a cascaded amplifier in decibels.

   An example of a 3 stage cascaded amplifier is shown on the right.



   When the individual stage gains are expressed in decibels, the total gain is found using the equation:

   $Av_{(T)} = Av_{(1)} + Av_{(2)} + Av_{(3)}$

4. Explain the significance of negative decibel values.

   A negative value in decibels indicates a loss (or attenuation) rather than a gain.

5. Measure the voltage gain of an amplifier and specify it in decibels.

   Use the process described on the last page of the Section 1 Summary but use the equation $Av_{(dB)} = 20Log\frac{Vout}{Vin}$ instead of $Av = \frac{Vout}{Vin}$.

Section 3

Objectives and Summary

1. Explain the terms *frequency response* and *bandwidth*

   Frequency response: How the amplifier's gain responds to input signals at different frequencies. This is usually graphed.

   Bandwidth: The width of the amplifier's pass-band. The bandwidth of an amplifier is calculated using the equation: $BW = f2 - f1$.

2. Calculate the output voltage of an amplifier at the lower and upper frequency roll-off points for a given input voltage and gain

   Use the review questions to practise this. The equation need for this purpose is:

   $$Vout_{(at\,f_n)} = 0.707 \times Vout_{(\max)}$$

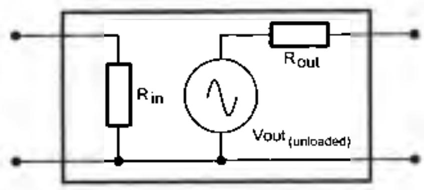
3. Describe a procedure for measuring the frequency response of an amplifier

   - Connect the CRO's channel 1 input to the amplifier's input and the channel 2 input to the amplifier's output.
   - Connect a sinewave generator to the amplifier's input (your set-up should now look like the diagram on the last page of the Section 1 Summary).
   - Adjust the input signal's amplitude so that the amplifier's output signal isn't clipping.
   - Measure the amplifier's input voltage.
   - Measure the amplifier's output voltage.
   - Calculate the amplifier's gain as a ratio (and convert to decibels if appropriate).
   - Repeat for at least ten frequencies at values appropriate for the circuit (for example, at 500Hz, 1kHz, 2kHz and so on).
   - Plot the results on a graph of frequency versus gain (or frequency versus output voltage) using log-linear graph paper.

Section 4

Objectives and Summary

1. Draw the equivalent model of a voltage amplifier and explain each part



- The input resistance (*Rin*) is the equivalent resistance that appears across the input terminals as "seen" by the signal source.
- From a "back-box" perspective, the output voltage of an amplifier can be thought of as being produced by a signal source inside the amplifier.
- The output resistance (*Rout*) is the equivalent resistance that appears across the output terminals as "seen" by the load looking back into the amplifier.

2. Explain the combined effect that an amplifier's output resistance and the load resistance have on the output voltage and voltage gain of an amplifier

The output resistance and load resistance combine to form a voltage divider. This forces the potential difference across the amplifier's output terminals to be smaller than when the load is not connected. This in turn means that the amplifier's gain is smaller than when the load is not connected.

3. Calculate the loaded output voltage and loaded voltage gain of an amplifier

Use the review questions to practise this. The equations are:

$$V_{RL} = Vout_{(unloaded)} \times \frac{R_L}{R_L + Rout}$$

$$Av_{(loaded)} = \frac{Vout_{(loaded)}}{Vin}$$

4. Explain the combined effect of an amplifier's input resistance and the signal source's output resistance on the input voltage to an amplifier

The amplifier's input resistance and the source's output resistance combine to form a voltage divider. This forces the potential difference across the amplifier's input terminals to be smaller than the source's unloaded output voltage. This doesn't affect gain. However, you do need to be aware of this as an issue because you could set the source up for a particular input voltage but, when you connect it to the amplifier, the source's voltage drops!

5. Calculate the loaded input voltage of an amplifier

   Use the review questions to practise this. The equation is:

   $Vin = V_S \times \frac{Rin}{Rin+R_S}$

6. State the ideal input and output resistances for a voltage amplifier

   The ideal input resistance for a voltage amplifier is infinity.

   The ideal output resistance for a voltage amplifier is zero.

Section 5

Objectives and Summary

1. List the characteristics of an ideal amplifier including voltage gain, input resistance, output resistance, distortion and bandwidth

   - Gain infinite
   - Bandwidth infinite
   - Input resistance infinite
   - Output resistance zero
   - Distortion zero

2. Give typical figures for the following op amp characteristics (open-loop mode): voltage gain, input resistance, output resistance and bandwidth

   - Gain at least 200,00
   - Bandwidth 10Hz
   - Input resistance at least 1MΩ
   - Output resistance at most 100Ω

3. Define the terms *open-loop mode* and *open-loop voltage gain*

   Open-loop mode is when the op amp has no electrical connection from its output back to its inverting input. This is the device's "natural" condition.

   Open-loop voltage gain is the op amp's "natural" voltage gain. That is, it's the op amp's voltage gain when there is no negative feedback. This is usually extremely large.

4. Explain the operation of an op amp operated in the open-loop mode

   The op amp amplifies the difference between the voltages on its non-inverting and inverting inputs.

5. Predict the output voltage of an op amp operated in the open-loop mode for given values of supply voltages and input voltages

   Use the review questions to practise this. The equation is:

   $Vout = (Vin_{non-inverting} - Vin_{inverting}) \times Av_{OL}$

6. Explain the operation of an op amp operated in open-loop mode to implement a comparator

   The comparator is an open-loop op amp circuit that amplifies the difference between the voltages on its non-inverting and inverting inputs. But, given the enormous voltage gain of op amps, the open-loop mode op amp is always overdriven and so output voltage is always only equal to one of the two power supply voltages (ie $+Vcc$ or $-Vcc$).

7. Predict the output voltage of a comparator given values for the supply voltages and input voltages

Input conditions	Output voltage
When $Vin_{non\text{-}inverting}$ is more positive than $Vin_{inverting}$	+Vcc
When $Vin_{non\text{-}inverting}$ is less positive than $Vin_{inverting}$	-Vcc

8. Give applications for comparators

   Comparators are excellent for detecting the difference between two conditions (ie light & dark, hot & cold, etc).

Section 6

Objectives and Summary

1. Define the terms *negative feedback*, *closed-loop mode*, *closed-loop voltage gain*, and *gain bandwidth product*

   Negative feedback in electronics is an electrical connection between a circuit's output back to its input in such a way that it subtracts some or all of the output from the input. With op amps, this is achieved by connecting the op amp's output back to its inverting input.

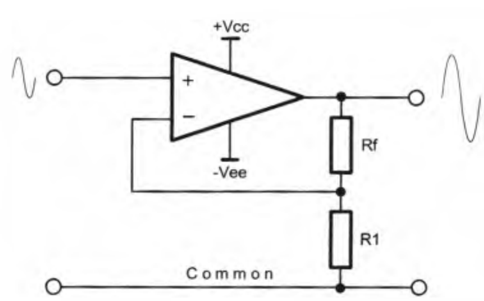
   Closed-loop mode is the mode of op amp operation when its in a circuit that has negative feedback.

   Closed-loop voltage gain (Av_{CL}) is the voltage gain of an amplifier with negative feedback.

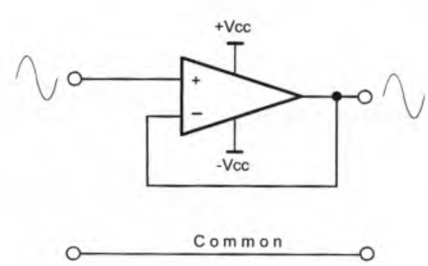
   Gain bandwidth product (*GBWP* or *UGBP*) is a constant that is calculated by multiplying an amplifier's closed-loop voltage gain with its closed-loop bandwidth.

2. Recognise the non-inverting amplifier and voltage follower op amp configurations in schematic diagrams

   Non-inverting amplifier



   Voltage follower



   Note: These two configurations can be drawn in other ways which can make them trickier to recognise. Examples are given in the review questions.

3. Calculate the closed-loop voltage gain of a non-inverting amplifier given the values of Rf and $R1$

   Use the review questions to practise this. The equation is:

   $Av_{CL} = (\frac{Rf}{R1}) + 1$.

4. Calculate a value for *Rf* or *R1* for a non-inverting amplifier given its closed-loop voltage gain and the value of the other resistor

   Use the review questions to practise this. The equations are:

   $R1 = \frac{Rf}{Av_{CL}-1}$ and $Rf = R1 \times (Av_{CL} - 1)$

5. Give typical values of input and output resistance for the non-inverting amplifier

   Rin is typically >1MΩ and *Rout* is typically <100Ω.

6. Calculate the closed-loop bandwidth of a non-inverting amplifier given its closed-loop voltage gain and the op amp's GBWP

   Use the review questions to practise this. The equation is:

   $BW_{CL} = \frac{GBWP}{Av_{CL}}$

7. Calculate an op amp's GBWP given a non-inverting amplifier's closed-loop voltage gain and closed-loop bandwidth

   Use the review questions to practise this. The equation is:

   $GBWP = Av_{CL} \times BW_{CL}$

8. State the voltage gain of the voltage follower

   One (1). (It's common to refer to this as "unity" gain.)

9. State the bandwidth of the voltage follower given the op amp's gain bandwidth product

   The voltage follower's bandwidth is the same as the op amp's GBWP (because the circuit's gain is 1).

10. Specify relative values of input and output resistance for the voltage follower

    This configuration's *Rin* is the highest of all op amp circuits and its *Rout* is the lowest.

11. Predict the type, magnitude and phase of the output voltage for both configurations given a set of input conditions

    Non-inverting amplifier: $Vout = Av_{CL} \times Vin$

    Voltage follower: $Vout = Vin$

12. Give applications for both op amp configurations

    Non-inverting: Amplify small signals in audio systems and instrumentation, etc.

    Voltage follower: As a buffer between an amplifier and its load to minimise the effect of loading.

13. Troubleshoot the non-inverting and voltage follower amplifiers

    The most important first step when testing any circuit that you suspect may be faulty is to check its power supply connections. If the op amp's power supply connections are correct, the circuit will almost certainly not perform as required.

    Once you've established that the power supply voltages are good, the next thing to do is measure the voltage on non-inverting and inverting pins (of the op amp itself) with respect to common.

    If they're the same then this tells you that negative feedback must be operating in the circuit. So, if there is a fault, it can only be: a) one of the two resistors has changed value; b) *R1* has gone open-circuit; or c) or there's no input signal (perhaps due to a cracked PCB track or dry-joint).

    If the two inputs are not exactly the same voltage then this tells you that negative feedback is not operating in the circuit. In which case, possible problems include: a) the op amp may be faulty; b) the feedback resistor is open-circuit; or c) the loop is broken for some other reason (perhaps due to a cracked PCB track or dry-joint).

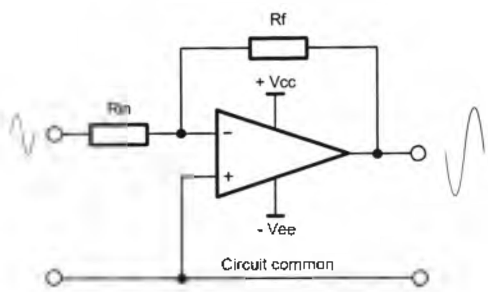
    The size and shape of the output voltage, combined with your knowledge of the operation of these circuits, will allow you to determine which of these possibilities is applicable.

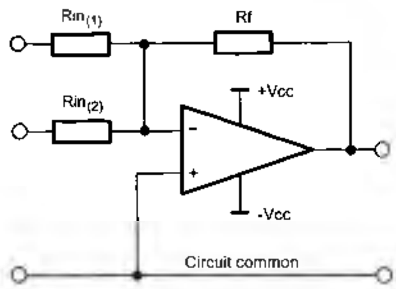
Section 7

Objectives and Summary

1. Recognise the inverting and summing op amp configurations in a schematic diagram

Inverting amplifier | Summing amplifier





Note: This summing amp is an example with two inputs but three or more inputs are possible.

2. Calculate the closed-loop voltage gain of an inverting amplifier given the values of *Rf* and *Rin*

Use the review questions to practise this. The equation is:

$$Av_{CL} = -\left(\frac{Rf}{Rin}\right)$$

3. Calculate a value for *Rf* or *Rin* for an inverting amplifier given its closed-loop voltage gain the value of the other resistor

Use the review questions to practise this. The equations are:

$Rin = \frac{Rf}{Av_{CL}}$ and $Rf = Rin \times Av_{CL}$

Note: Drop the gain's minus sign when using this equation.

4. Calculate the closed-loop bandwidth of an inverting amplifier given its closed-loop voltage gain and the op amp's GBWP

   Use the review questions to practise this. The equation is:

   $BW_{CL} = \frac{GBWP}{Av_{CL}}$ **Note:** Drop the gain's minus sign when using this equation.

5. Calculate an op amp's GBWP given an inverting amplifier's closed-loop voltage gain and closed-loop bandwidth

   Use the review questions to practise this. The equation is:

   $GBWP = Av_{CL} \times BW_{CL}$ **Note:** Drop the gain's minus sign when using this equation.

6. Give typical values of input and output resistance for the inverting amplifier configuration

   The input resistance is always the same as the value of the *Rin* resistor (which should only be a value to a maximum of about 20kΩ) and *Rout* is typically <100Ω

7. Give applications for the inverting op amp configuration

   Amplify small signals in audio systems and instrumentation, etc.

8. Predict the type, magnitude and phase of the output voltage for the inverting and summing amplifier configurations given a set of input conditions

   Use the review questions to practise this. The equations are:

   Inverting amp:

   $Vout = Av_{CL} \times Vin$

   Summing amp:

   $Av_{(n)} = \left(\frac{Rf}{Rin_{(n)}}\right)$

   $Vout_{(n)} = Vin_{(n)} \times Av_{(n)}$

   $Vout = Vout_{(1)} + Vout_{(2)} + Vout_{(n)}$

9. Give applications for the summing op amp configuration

   Audio mixer, digital-to-analog converter

10. Troubleshoot the inverting and summing amplifiers

    The most important first step when testing any circuit that you suspect may be faulty is to check its power supply connections. If the op amp's power supply connections are correct, the circuit will almost certainly not perform as required.

    Once you've established that the power supply voltages are good, the next thing to do is measure the voltage on non-inverting and inverting pins (of the op amp itself) with respect to common.

    If the two inputs have exactly the same voltage **and** are zero volts then this tells you that negative feedback must be operating in the circuit. So, if there is a fault, it can only be: a) one of the two resistors has changed value; b) *Rin* has gone open-circuit; or c) there's no input signal (perhaps due to a cracked PCB track or dry-joint).

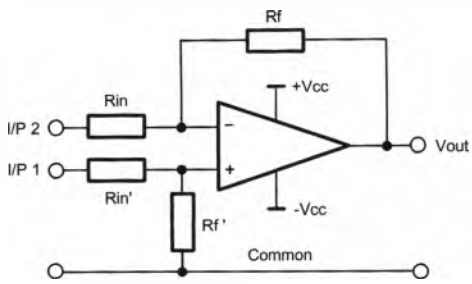
    However, if the inverting input is not exactly 0V then this tells you that negative feedback is not operating in the circuit. In which case, possible problems include: a) the op amp may be faulty; b) the feedback resistor is open-circuit, or c) the loop is broken for some other reason (perhaps due to a cracked PCB track or dry-joint).

    The size and shape of the output voltage, combined with your knowledge of the operation of these circuits, will allow you to determine which of these possibilities is applicable.

Section 8

Objectives and Summary

1. Recognise the differencing amplifier op amp configuration in a schematic diagram



2. Predict the type, magnitude and phase of the output voltage for the differencing amplifier given a set of input conditions

   Use the review questions to practise this. The equation is:

   $$Vout = (Vin_{(1)} - Vin_{(2)}) \times \frac{Rf}{Rin}$$

3. Give applications for the differencing amplifier

   Noise rejection for signals on balanced transmission lines

4. Give reasons for why faulty op amps may sometimes need to be replaced by a suitable substitute instead of the original part

   i) When the repair is urgent and the original part is not readily available
   ii) When the equipment is older and the original part is no-longer available

5. Choose a suitable replacement op amp using a table of manufacturers' data basing your decision on the following op amp parameters: power supply requirements; GBWP; frequency compensation; and pinout.

   - Power supply requirements

     If the original part requires a dual rail power supply then the substitute must do too. Similarly, if the original requires a single rail power supply then the substitute must do too. For both types, the substitute must be able to operate from the power supply voltages of the original's in-circuit rail voltages.

   - GBWP

     The GBWP of the substitute should be the about same or higher than the original.

   - Frequency compensation

     If the original is frequency compensated then the substitute must be also. Similarly, if the original is not frequency compensated then the substitute must not be either.

   - Pinout

     Ideally the pinout of the substitute should be the same as the original otherwise modification of the circuit board would be required which is best avoided.

Appendix 2

Sample final theory test (with answers)

The following is a sample final theory test that you can use to prepare for the actual final theory test for this subject. Although the questions are different, the content assessed and level of difficulty are the same.

A suggested way of using this test:

- Study this subject.
- On the weekend before the actual final theory test, sit down and do this sample as though it is a real test. That is;
  - Turn off your mobile phone
  - Sit down in a quiet room and ask not to be disturbed for the duration of the test
  - Attempt the test without looking at the answers
- Once you have finished the test and checked your answers, mark the test.
- Use your mark as a guide to your knowledge about this subject.
  - In most cases, the mark you get for this test (after following the procedure above) is the kind of mark you can expect for the actual final theory test
  - In the precious time you have left, study the topic areas that you did poorly on in the sample test

EC0067 - Amplifier Fundamentals

Final Theory Exam (Sample)

Time allowed: 2 hours

Instructions

- The total number of marks available is 91.
- Each question is worth 1 mark.
- Where calculations are involved it is recommended that you show your working.
- Do not mark this exam paper.

Part A - Multiple choice questions

1. The current out of an amplifier comes from

   a) the power supply only.
   b) the input signal only.
   c) both the power supply and the input signal.
   d) the little signal generator inside the amplifier.

2. What is the voltage gain of the amplifier in Figure 1?

   a) 1.18×10^{-3}
   b) 8.5
   c) 850
   d) 85.1

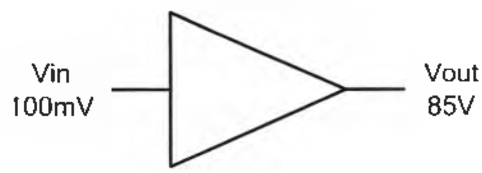


Figure 1

3. What is *clipping*?

   a) A method of protecting speakers from over-voltages
   b) An unwanted phase inversion of the output signal
   c) A method of protecting amplifiers from being over-driven
   d) A type of distortion of amplifier output signals

4. To determine whether or not amplifier will clip, all that you need to know is

   a) the size of the amplifier's input signal.
   b) the size of the amplifier's gain.
   c) the size of the amplifier's power supply voltage.
   d) the size of the amplifier's input signal, gain and power supply voltage.

5. Clipping occurs because

   a) the input signal is too big.
   b) the gain of the amplifier is too big.
   c) the power supply voltage is too big.
   d) the power rating of the amplifier is too big.

6. What is the current gain of the amplifier in Figure 2?

   a) 1,200
   b) 0.0147
   c) 0.00083
   d) 4.2035

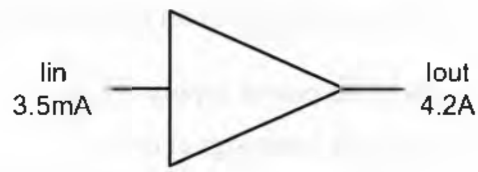


Figure 2

7. An amplifier has a gain of -50. The negative sign means that the output signal is

   a) smaller than the input signal.
   b) phase inverted.
   c) bigger than the input signal.
   d) less that the power supply voltage.

8. An amplifier has a gain of -25dB. The negative sign means that the output signal is

   a) smaller than the input signal.
   b) phase inverted.
   c) bigger than the input signal.
   d) less that the power supply voltage.

Questions 9 to 11 refer to the circuit in Figure 3 below

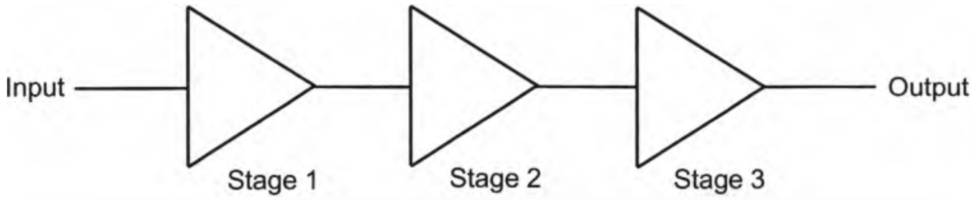


Figure 3

9. This arrangement of amplifiers is known as a

   a) threaded amplifier.
   b) cascaded amplifier.
   c) staged amplifier.
   d) staggered amplifier.

10. What is the total gain of the arrangement if the individual stage gains are 12, -17 and 5?

   a) -34
   b) 34
   c) -1,020
   d) 1,020

11. What is the total gain of the arrangement if the individual stage gains are -6dB, 22dB and 34dB?

   a) 50dB
   b) 56dB
   c) -62dB
   d) 62dB

12. What is the power gain of the amplifier in Figure 4?

   a) 60.000055
   b) 0.0033
   c) 0.000000917
   d) 1,090,909

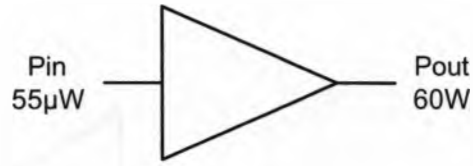


Figure 4

13. To calculate the voltage gain of an amplifier using measured input and output signals,

   a) you must use RMS voltages.
   b) you must use peak voltages.
   c) you must use peak-to-peak voltages.
   d) you can use any form of voltage as long as you use the same form for both signals.

14. What is the gain in decibels of an amplifier with a power gain of 15,750?

   a) 42dB
   b) 84dB
   c) 5.2dB
   d) 5.5dB

15. What is the gain in decibels of an amplifier with a current gain of 820?

   a) 29.1dB
   b) 58.3dB
   c) 3.9dB
   d) 4.2dB

16. What is the output voltage of the amplifier in Figure 5?

   a) 341μV
   b) 2935V
   c) 6.21V
   d) 46mV

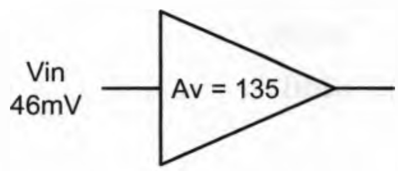


Figure 5

Questions 17 to 21 refer to the graph of an amplifier's frequency response in Figure 6 below

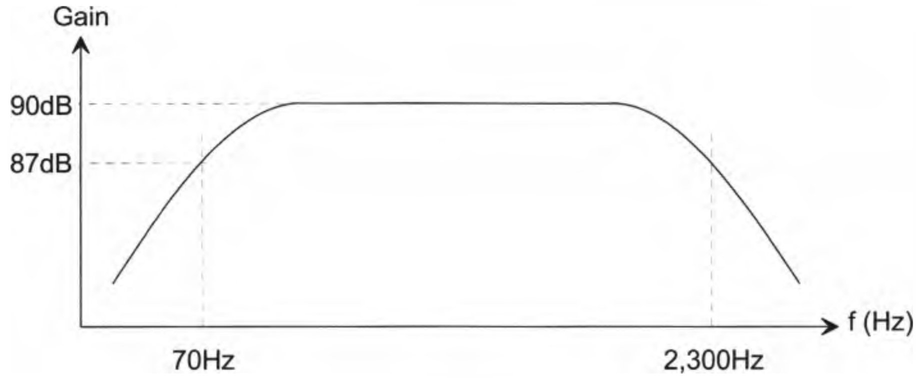


Figure 6

17. What is the mid-band gain of the amplifier?

    a) 90dB
    b) 87dB
    c) 2.3kHz
    d) 70Hz

18. What is the gain of the amplifier at *f1*?

    a) 90dB
    b) 87dB
    c) 2.3kHz
    d) 70Hz

19. What is the *f2* frequency?

    a) 90dB
    b) 87dB
    c) 2.3kHz
    d) 70Hz

20. What is the amplifier's bandwidth?

    a) 2.37kHz
    b) 70Hz
    c) 2.23kHz
    d) 2.3kHz

21. Which of the following frequencies is **not** a mid-band frequency of the amplifier?

    a) 2.7kHz
    b) 2kHz
    c) 630Hz
    d) 100Hz

22. What is the output power of the amplifier.in Figure 7?

    a) 15.2nW
    b) 52μW
    c) 65,577,000W
    d) 177mW

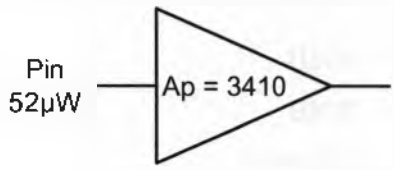


Figure 7

23. Which of the following is the best output resistance for a voltage amplifier driving a 1kΩ load?

    a) 100Ω
    b) 1kΩ
    c) 10kΩ
    d) 1MΩ

24. Which of the following is the best input resistance for a voltage amplifier supplied by a 5kΩ source?

    a) 100Ω
    b) 1kΩ
    c) 10kΩ
    d) 1MΩ

25. What is the output current of the amplifier in Figure 8?

a) 747A
b) 16.8A
c) 1.34mA
d) 112A

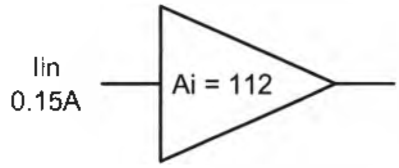


Figure 8

26. The loaded gain of an amplifier

a) is exactly the same as the unloaded gain.
b) is always bigger than the unloaded gain.
c) is always smaller than the unloaded gain.
d) may be bigger or smaller than the unloaded gain depending on the resistances involved.

27. Amplifier gain figures are often quoted in decibels instead of as a ratio because

a) they are easier to graph.
b) our hearing response is logarithmic.
c) it's a more technical approach.
d) speaker ratings are in decibels.

28. What is the input voltage of the amplifier in Figure 9?

a) 262mV
b) 17V
c) 65V
d) 1,105V

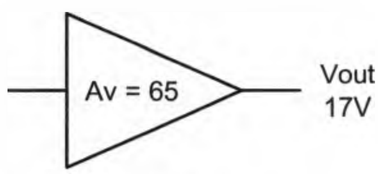


Figure 9

29. Which of the following characteristics does the **ideal** amplifier have?

a) A distortion figure of 100%
b) An infinite output resistance
c) An infinite bandwidth
d) Zero input resistance

30. Which op amp is the most suitable substitute for the LM741 according to the data in Table 1?

 a) LM301
 b) ADC8506
 c) LM10C
 d) TL071

31. Which op amp is the most suitable substitute for the CA3130?

 a) CA3140
 b) NE5534
 c) LM10C
 d) None of the above

Table 1

Type	Device	UGBP (MHz)	Slew Rate (V/µS)	Supply voltage		CMRR (dB)	Internal Freq. Comp.
				Min	Max		
AD8506	Low current input	95k	13m	±0.9V	±2.5V	105	Yes
LM301	GP Amp	1	0.5	±3V	±18V	70	No
LM741	GP Amp	1	0.5	±3V	±18V	70	Yes
LTC2057	Low Dift	1.5	0.45	±4.75V	±36V	150	Yes
NE5534	Low noise	10	6	±3V	±22V	70	No
MAX9943	Precision	2.4	0.35	+6V	+38V	125	Yes
TL071	JFET low noise	3	13	±3.6V	±18V	70	Yes
MC3317	Low power	1.8	2.1	±1.5V	±22V	90	Yes
CA3130	MOSFET input	4	10	±2.5V	±8V	70	No
CA3140	MOSFET input	4.5	9	±2V	±18V	70	Yes
LM10C	Inc. voltage ref.	0.1	*	+1.1V	+45V	87	Yes

32. What is the input current of the amplifier in Figure 10?

    a) 110mA
    b) 9.1A
    c) 30A
    d) 99A

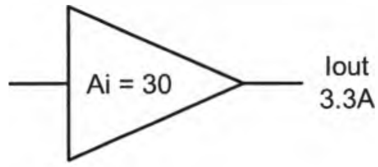


Figure 10

33. Which of the following circuits operates the op amp in the open-loop mode?

    a) The non-inverting amplifier
    b) The inverting amplifier
    c) The differencing amplifier
    d) The comparator

34. What is the input power of the amplifier in Figure 11?

    a) 200kW
    b) 20W
    c) 50mW
    d) 5mW

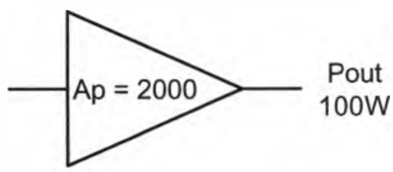


Figure 11

35. The specifications of op amps approach the ideal for all characteristics except the

    a) distortion figure.
    b) gain.
    c) input resistance.
    d) bandwidth.

36. What is the gain as a ratio of an amplifier with a voltage gain of 42dB?

    a) 15,849
    b) 126
    c) 1×10^{41}
    d) 5×10^{40}

37. What is the gain as a ratio of an amplifier with a power gain of 70dB?

    a) 10,000,000
    b) 3,162
    c) 1×10^{69}
    d) 5×10^{68}

38. What happens to the output voltage of an amplifier when the load is disconnected?

    a) It always goes up, even if it's just by a small amount
    b) It always goes down, even if it's just by a small amount
    c) It stays exactly the same
    d) It may go up or down depending on the value of the resistances involved

39. The frequency response of a closed-loop op amp circuit is

    a) always equal to the gain bandwidth product (GBWP).
    b) goes up as closed-loop gain goes up.
    c) goes up as closed-loop gain goes down.
    d) equal to the open-loop bandwidth of the op amp.

Part B - Short answer questions and calculations

40. Name **two** devices that can be connected to the input of an amplifier.

41. Name **two** devices that can be connected to the output of an amplifier.

42. List the test equipment needed to perform a frequency response test on an amplifier.

Questions 43 to 46 refer to Figure 12

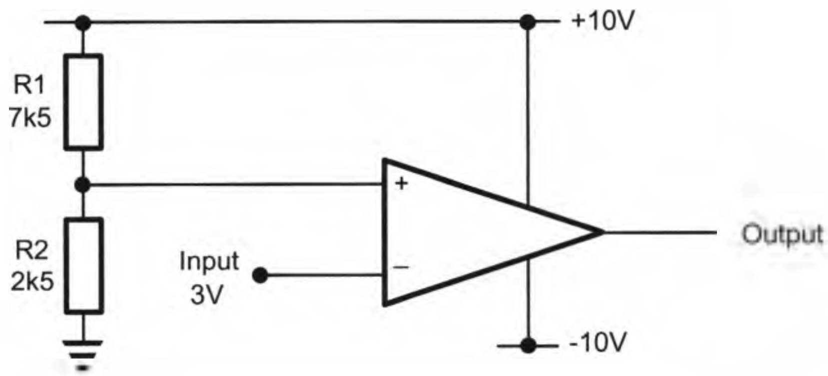


Figure 12

43. What is the name of this circuit?

44. What is the voltage on the op amp's non-inverting input?

45. What is the voltage on the op amp's output?

46. What would you expect to see on the output of the circuit if a 7Vp-p sinewave was connected to the input?

Questions 47 to 54 refer to Figure 13

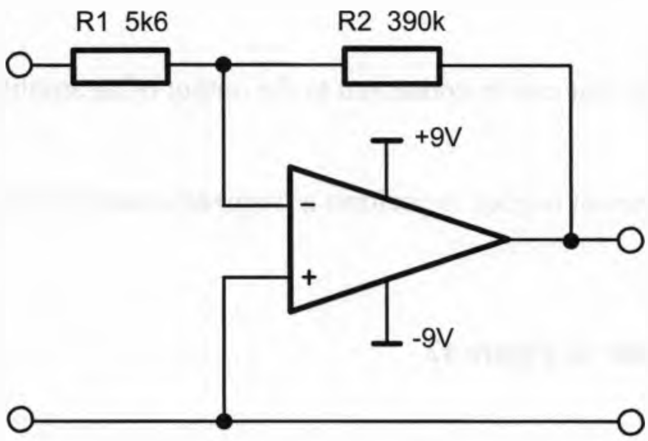


Figure 13

47. What is the name of this circuit?

48. What is the amplifier's voltage gain?

49. What would be the size of the output signal for a 80mVp-p input signal?

50. What is the phase relationship between the input and output signals?

51. What is the maximum peak-to-peak output voltage before clipping would occur?

52. What is the maximum allowable input voltage without over-driving the amplifier?

53. What is the amplifier's input resistance?

54. What is the amplifier's bandwidth if the op amp's GBWP is 5MHz?

Questions 55 to 58 refer to Figure 14

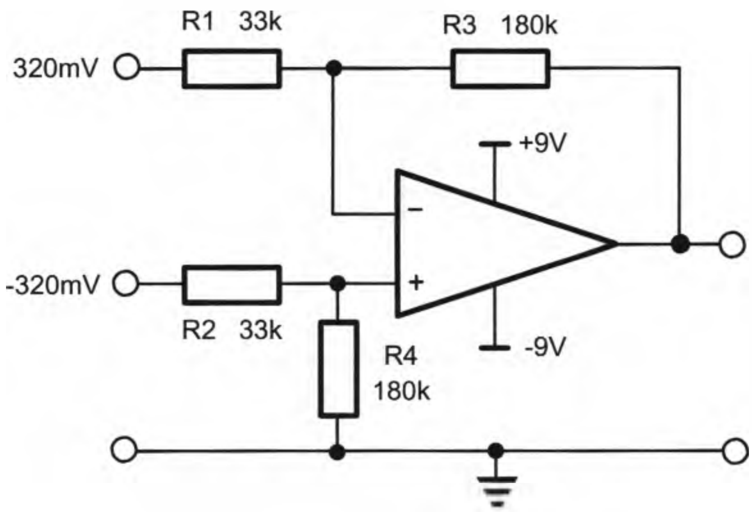


Figure 14

55. What is the name of this circuit?

56. What is the amplifier's voltage gain?

57. What is the output voltage for the DC input voltages shown.

58. What is the maximum allowable potential difference between the circuit's two inputs?

Questions 59 to 67 refer to Figure 15

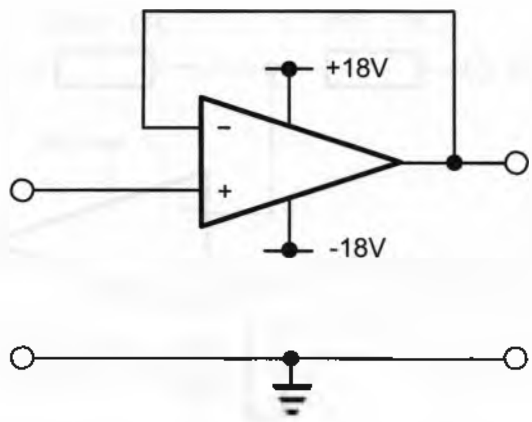


Figure 15

59. What is the name of this circuit?

60. What is the amplifier's voltage gain?

61. What would be the size of the output signal for a 750mVp-p input signal?

62. What is the phase relationship between the input and output signals?

63. What is the maximum peak-to-peak output voltage before clipping would occur?

64. What is the maximum allowable input voltage without over-driving the amplifier?

65. What is the bandwidth if the op amp's GBWP is 3MHz?

66. What are two advantages of this circuit when compared to other op amp configurations?

67. What is one disadvantage of this circuit when compared to other op amp configurations?

Questions 68 to 74 refer to Figure 16

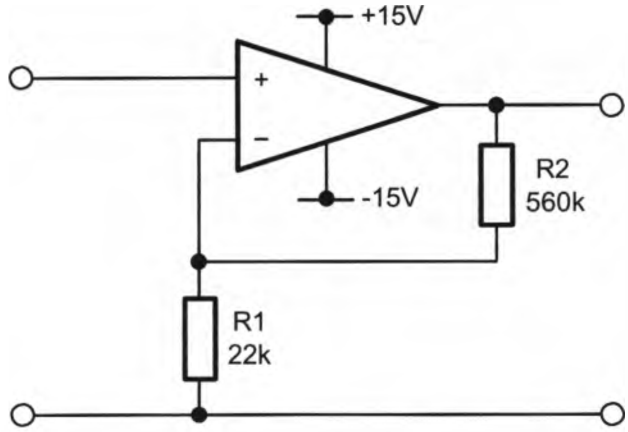


Figure 16

68. What is the name of this circuit?

69. What is the amplifier's voltage gain?

70. What would be the size of the output signal for a 350mVp-p input signal?

71. What is the phase relationship between the input and output signals?

72. What is the maximum peak-to-peak output voltage before clipping would occur?

73. What is the maximum allowable input voltage without over-driving the amplifier?

74. What is the bandwidth if the op amp's GBWP is 8MHz?

Questions 75 to 77 refer to Figure 17

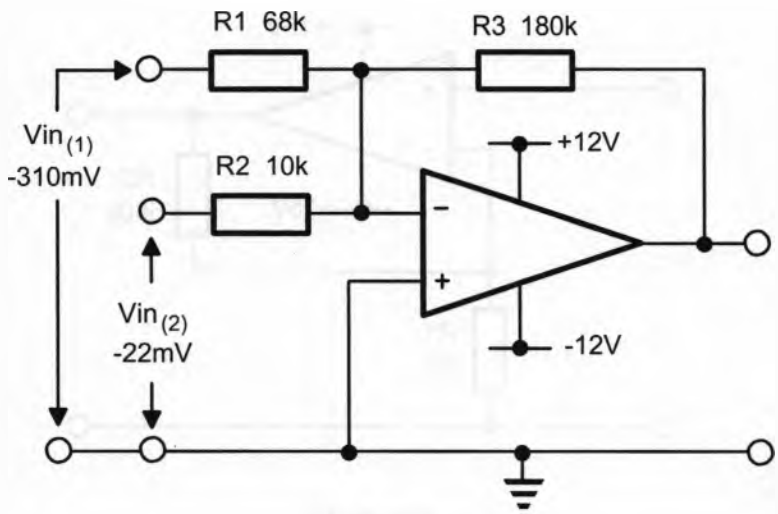


Figure 17

75. What is the name of this circuit?

76. What is the output voltage for the input voltages shown.

77. Give one application for this circuit?

78. What value of resistance does *R1* in Figure 18 below need to be for the circuit to have a gain of -13?

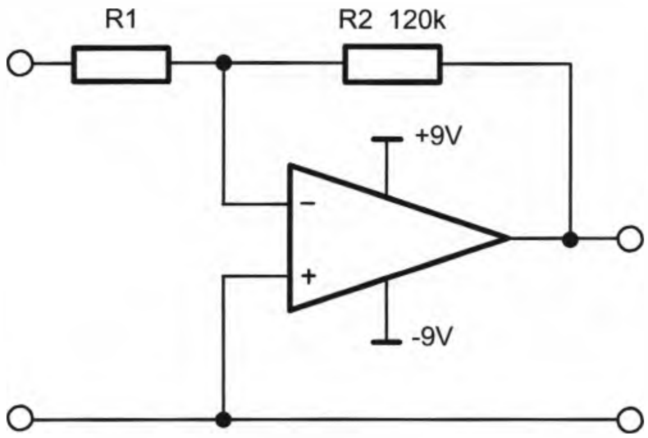


Figure 18

79. What value of resistance does *R2* in Figure 19 below need to be for the circuit to have a gain of 80?

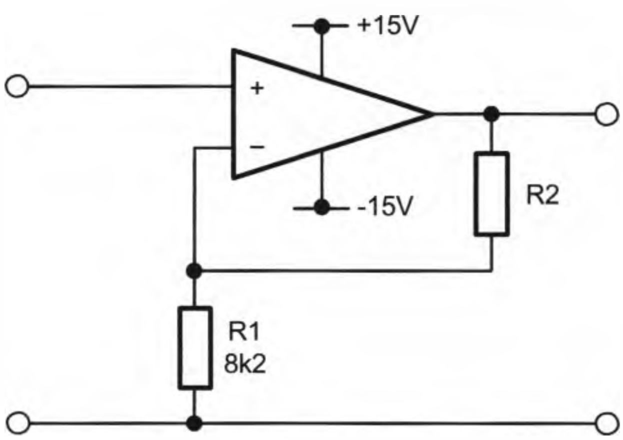


Figure 19

Questions 80 to 89 refer to Figure 20

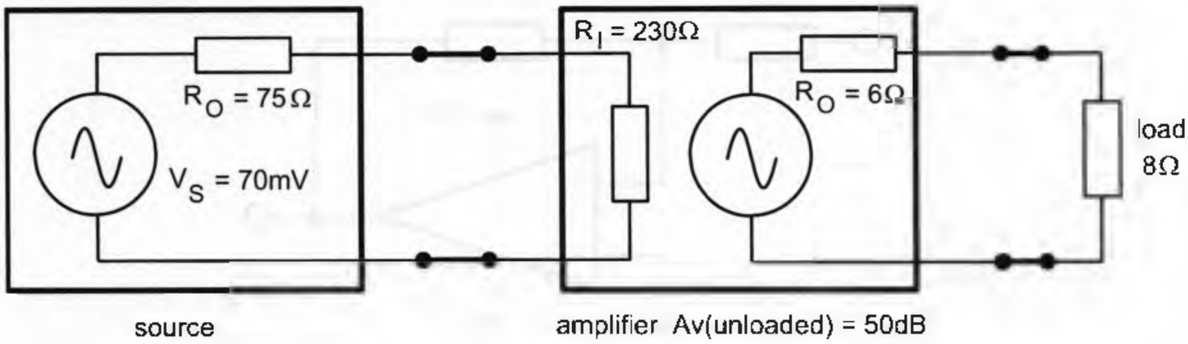


Figure 20

80. What is the **unloaded** output voltage of the **source**?

81. What is the amplifier's input voltage?

82. What is the amplifier's **unloaded** output voltage?

83. What is the amplifier's **loaded** output voltage?

84. What is the amplifier's loaded voltage gain as a ratio?

85. What is the amplifier's loaded voltage gain expressed in decibels?

86. What is the amplifier's input power?

87. What is the amplifier's output power?

88. What is the amplifier's power gain as a ratio?

89. What is the amplifier's power gain expressed in decibels?

90. What value of resistance does *R2* in Figure 18 below need to be for the circuit to have a gain of -138?

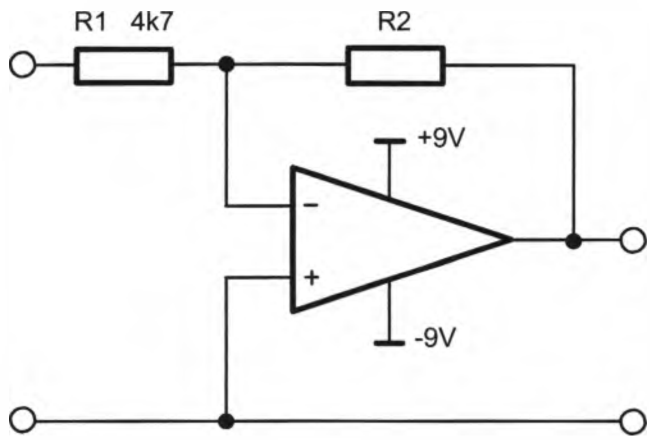


Figure 21

91. What value of resistance does *R1* in Figure 19 below need to be for the circuit to have a gain of 17?

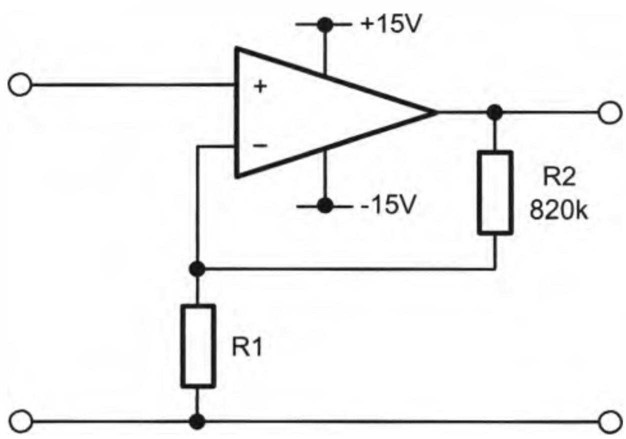


Figure 22

End of exam

Answers to Sample Final Theory Test

1. A
2. C
3. D
4. D
5. A
6. A
7. B
8. A
9. B
10. C
11. A
12. D
13. D
14. A
15. B
16. C
17. A
18. B
19. C
20. C
21. A
22. D
23. A

24. D

25. B

26. C

27. B

28. A

29. C

30. D

31. D

32. A

33. D

34. C

35. D

36. B

37. A

38. A

39. C

40. Any two of: a microphone, an antenna, the pick-up on a musical instrument, a hi-fi component (such as a CD player), another amplifier.

41. Any two of: a loud speaker, an antenna or the input of another circuit (such as another amplifier).

42. A function (or signal) generator and a CRO

43. A comparator (with reference voltage)

44. 2.5V

45. -10V

46. A 20Vp-p (or ±10Vpk) squarewave

47. Inverting amplifier
48. -69.6
49. 5.57Vp-p
50. Inverted
51. 18V (or ±9Vpk)
52. 258.5mVp-p
53. 5k6Ω
54. 71.79kHz
55. Differencing amplifier
56. 5.45
57. -3.49V
58. Either +1.65V or -1.65V
59. Voltage Follower or Buffer
60. 1
61. 750mVp-p
62. In-phase
63. 36Vp-p (or ±18Vpk)
64. 36Vp-p (or ±18Vpk)
65. 3MHz
66. Very large input resistance and very low output resistance
67. No gain
68. Non-inverting amplifier
69. 26.45
70. 9.26Vp-p

71. In-phase

72. 30Vp-p (or ±15Vpk)

73. 1.13Vp-p

74. 302.4kHz

75. Summing amplifier

76. 1.22V

77. Mixer or DAC

78. 9.23kΩ

79. 647.8kΩ (Note: 656kΩ is wrong!)

80. 70mV

81. 52.79mV

82. 16.69V

83. 9.54V

84. 180.7

85. 45.14dB

86. 12.12μW

87. 11.38W

88. 938,651

89. 59.7dB

90. 648.6kΩ

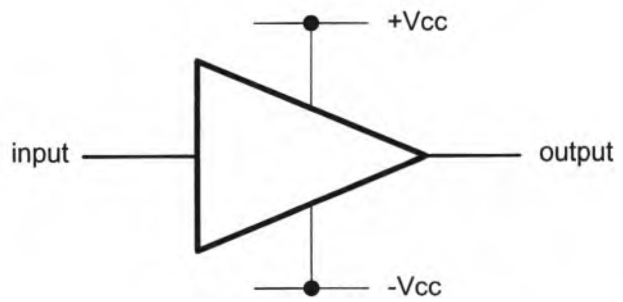
91. 51.25kΩ (Note: 48.235kΩ is wrong!)

End of answers :-)

Answers to Review Questions

Section 1

1.



2. Refer to the diagram above.

3. Amplifiers cannot make electrical energy. The extra voltage/current needed for the output to be bigger than the input comes from a separate DC power supply.

4.
   (a) a microphone is an **input** device
   (b) a speaker is an **output** device
   (c) a signal generator is connected to the **input** of an amplifier
   (d) a 5W resistor could be connected to the **output** of an amplifier (as a *dummy-load* instead of a speaker)
   (e) another amplifier could be connected to either the **input** or the **output** of an amplifier.
   (f) a tape deck is connected to the **input** of an amplifier.

5. $Av = \frac{Vout}{Vin}$

   $Av = \frac{850mV}{10mV}$

   $Av = 85$

6. $Vout = Av \times Vin$

   $Vout = 40 \times 100mV$

   $Vout = 4V$

Section 1 (continued)

7. $Vin = \frac{Vo}{Av}$

$Vin = \frac{3V}{120}$

$Vin = 25mV$

8. $A_I = \frac{Iout}{Iin}$

$A_I = \frac{500mA}{2mA}$

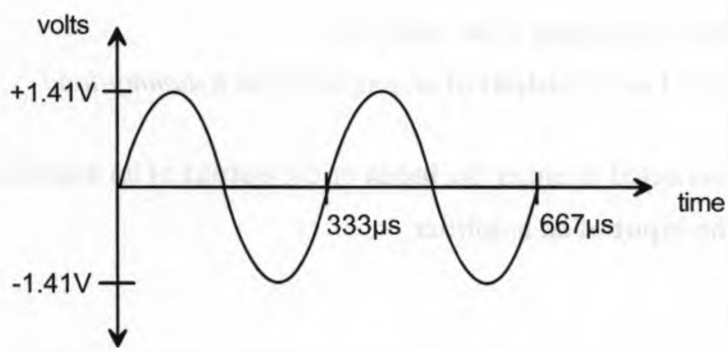
$A_I = 250$

9. $Pin = Iin \times Vin$ $\quad Pout = Iout^2 \times R_L$ $\quad A_P = \frac{Pout}{Pin}$

$Pin = 20\mu A \times 1V$ $\quad Pout = 2A^2 \times 8\Omega$ $\quad A_P = \frac{32W}{20\mu W}$

$Pin = 20\mu W$ $\quad Pout = 32W$ $\quad A_P = 1,600,000$

10.



11. The negative sign in front of a gain (expressed as a ratio) means that the output is phase inverted.

Section 1 (continued)

12. First convert the input voltage to a peak-to-peak value:

$Vin_{(p-p)} = 2 \times (V_{RMS} \times 1.414)$

$Vin_{(p-p)} = 2 \times (20mV \times 1.414)$

$Vin_{(p-p)} = 56.56mV$

Then find the gain…

$Av = \frac{Vout}{Vin}$

$Av = \frac{15V}{56.56mV}$

$Av = 265$

13. $Av_{(T)} = Av_{(1)} \times Av_{(2)} \times Av_{(3)}$

$Av_{(T)} = 10 \times 5 \times 15$

$Av_{(T)} = 750$

14. $Av_{(T)} = Av_{(1)} \times Av_{(2)} \times Av_{(3)}$

$Av_{(T)} = -7 \times 13 \times -4$

$Av_{(T)} = 364$

15. In phase. There are two stages that introduce inversion which cancel each other out.

Section 2

1. $A_{P(dB)} = 10Log\left(\frac{Pout}{Pin}\right)$

$$A_{P(dB)} = 10Log\left(\frac{10W}{5mW}\right)$$

$$A_{P(dB)} = 10Log2000$$

$$A_{P(dB)} = 10 \times 3.3$$

$$A_{P(dB)} = 33dB$$

2. Transposing the equation $A_{P(dB)} = 10Log\left(\frac{Pout}{Pin}\right)$ to make Pout the subject gives:

$$Pout = Log^{-1}\left(\frac{A_{P(dB)}}{10}\right) \times Pin$$

$$Pout = Log^{-1}\left(\frac{63dB}{10}\right) \times 150\mu W$$

$$Pout = Log^{-1}6.3 \times 150\mu W$$

$$Pout = 1,995,262 \times 150\mu W$$

$$Pout = 299W$$

3. Transposing the equation $Av_{(dB)} = 20Log\left(\frac{Vout}{Vin}\right)$ to make Pout the subject gives:

$$Vin = \frac{Vout}{Log^{-1}\left(\frac{Av_{(dB)}}{20}\right)}$$

$$Vin = \frac{40Vp\text{–}p}{Log^{-1}\left(\frac{45dB}{20}\right)}$$

$$Vin = \frac{40Vp\text{–}p}{Log^{-1}2.25}$$

$$Vin = \frac{40Vp\text{–}p}{177.8}$$

$$Vin = 225mVp - p$$

Section 2 (continued)

4. The output signal will be clipped at the top and bottom.

5. $Av_{(1)} = 20dB$
$Av_{(2)} = 23.5dB$
$Av_{(3)} = 26dB$

6. $Av_T = Av_{(1)} + Av_{(2)} + Av_{(3)}$

$Av_T = 20dB + 23.5dB + 26$

$Av_T = 69.5dB$

7. $Av_T = Log^{-1}(\frac{Av_{(dB)}}{20})$

$Av_T = Log^{-1}(\frac{69.5dB}{20})$

$Av_T = 2,985$

8.

dB	Power gain	Voltage gain
3dB	2	1.41
6dB	3.98	2
20dB	100	10
-3dB	0.5	0.707
-13dB	0.05	0.22
-29dB	0.0013	0.035

9. The negative sign in front of a value in decibels indicates that the output is attenuated (smaller than the input). Note: it doesn't indicate a phase inversion between input and output.

Section 3

1. The width of the band of frequencies over which the amplifier's frequency response is maximum and flat.

2. Midband frequency

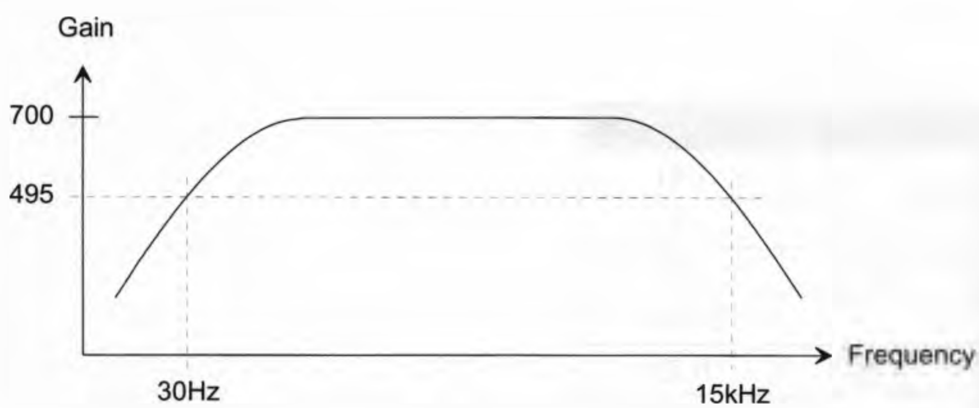
3. Upper and lower frequency roll-off points
   -3dB points
   Half-power points
   Break points
   Cut-off frequencies

4. It makes the slope at the upper end of the frequency response look the same as the lower end because the slope is constant per "decade".

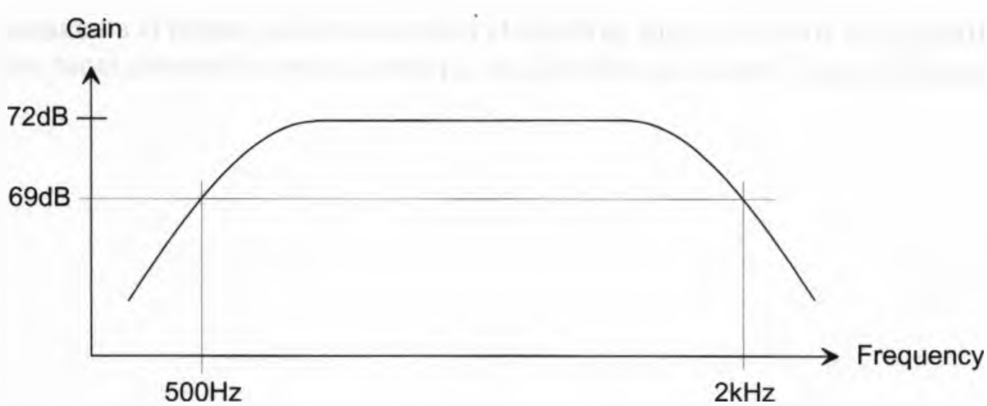
5. Because this is the point at which the power has dropped by half and the change can be heard by the human ear.

6. Because at *f1* and *f2* the output voltage has dropped to 0.707 of the voltage in the flat part of the response, and a drop of this amount is -3dB.

7.



8.



Section 4

1. True

2. True

3. $Vin = V_S \times \frac{Rin}{Rin+R_S}$

   $Vin = 100mV \times \frac{5k\Omega}{5k\Omega+600\Omega}$

   $Vin = 89.3mV$

4. Makes R_S smaller
   Make *Rin* bigger

5. $V_L = V_S \times \frac{R_L}{R_L+Rout}$

   $V_L = 2V \times \frac{8\Omega}{8\Omega+1\Omega}$

   $V_L = 1.78V$

6. Make *Rout* smaller
   Make R_L bigger

7. (a)

   $Vin = V_S \times \frac{Rin}{Rin+R_S}$

   $Vin = 100mV \times \frac{1k2\Omega}{1k2\Omega+75\Omega}$

   $Vin = 94.1mV$

   (b)

   $Vo_{(U/L)} = Vin \times Av$

   $Vo_{(U/L)} = 94.1mV \times 39.8$ [Note: 39.8 is the amplifier's gain as a ratio!]

   $Vo_{(U/L)} = 3.75V$

Section 4 (continued)

7. (c)

$$Vo_{(L)} = Vo_{(U/L)} \times \frac{R_L}{R_L+Rout}$$

$$Vo_{(L)} = 3.75V \times \frac{10\Omega}{10\Omega+3\Omega}$$

$$Vo_{(L)} = 2.88V$$

(d)

$$Av_{(loaded)} = \frac{V_L}{V_S}$$

$$Av_{(loaded)} = \frac{2.88V}{94.1mV}$$

$$Av_{(loaded)} = 30.6$$

$$Av_{(dB)} = 20Log30.6$$

$$Av_{(dB)} = 29.7dB$$

8. (a)

$$Pin = \frac{Vin^2}{Rin}$$

$$Pin = \frac{94.1mV^2}{1.2k\Omega}$$

$$Pin = 7.38\mu W$$

(b)

$$Pout = \frac{V_L^2}{R_L}$$

$$Pout = \frac{2.88V^2}{10\Omega}$$

$$Pout = 829mW$$

Section 4 (continued)

8. (c)

$$A_{P(dB)} = 10Log\left(\frac{Pout}{Pin}\right)$$

$$A_{P(dB)} = 10Log\left(\frac{829mW}{7.38\mu W}\right)$$

$$A_{P(dB)} = 50.5dB$$

9. The loaded gain will increase also.

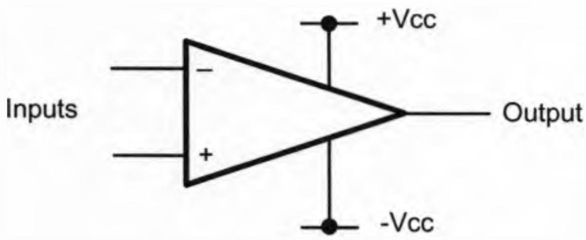
10. 61.7dB

11. 74.7dB

Section 5

1. Infinite voltage gain
   Infinite input resistance
   Infinite bandwidth
   Zero output resistance
   Zero distortion

2.



3. Bandwidth - 10Hz

4. The gain of the op-amp with no negative feedback.

5. 100,000 to 4,000,000 (The Av_{OL} for a 741 is 200,000)

6. The gain is so high that even relatively small input signals (say 1mV) will overdrive the amplifier. Also, the bandwidth is so narrow that they could only be used to amplify very low frequency signals (about 10Hz and under) and DC voltages.

7. Lower

8. The power supply voltages. For example, if the rail voltages are +10V and -10V then the maximum theoretical output voltage is ±10V (which would be 20Vp-p).

9. To allow the output voltage to swing above and below zero volts.

10.

Non-inv. input	Inverting input	Output
1V	500mV	+9V
750mV	1.5V	-9V
-400mV	-700mV	+9V
-2.5V	3V	-9V

Section 5 (continued)

11. $V_{ref} = V_{RR} \times \frac{R2}{R1+R2}$

$$V_{ref} = -5V \times \frac{2k2\Omega}{1k5\Omega+2k2\Omega}$$

$$V_{ref} = -2.97V$$

Input voltage V(+)	Reference voltage V(-)	Output Voltage
3V	-2.97V	+15V
-3V	-2.97V	-15V
-5V	-2.97V	-15V

Section 6

1. Non-inverting op amp.

2. $Av = \left(\frac{Rf}{R1}\right) + 1$

   $Av = \left(\frac{470k\Omega}{22k\Omega}\right) + 1$

   $Av = 22.4$

3. They are in phase with each other.

4. $\pm$15V or 30Vp-p (though, in practise, a little less).

5. $Vin_{(\max)} = \frac{Vout_{(\max)}}{Av}$

   $Vin_{(\max)} = \frac{30Vpp}{22.4}$

   $Vin_{(\max)} = 1.34Vpp$

6. 1MΩ

7. $BW = \frac{GBWP}{Av}$

   $BW = \frac{3MHz}{22.4}$

   $BW = 134kHz$

8. 2V

9. With an input signal the output would be a squarewave because, without negative feedback, the gain of the circuit is the same as the op amp's open-loop gain (which is enourmous) and so the amplifier would be being overdriven.

10. Buffer or Voltage Follower.

11. Av = 1

12. The input and output voltages are in phase with each other.

13. ±9V or 18Vp-p (though, in practise, a little less).

14. ±9V or 18Vp-p

Section 6 (continued)

15. Extremely high. The exact value can be calculated but doing so is beyond the scope of this subject.

16. 2.5MHz

17. 2V

18. *Rf* has gone open-circuit.

19. The output voltage has gone up to $+Vcc$ (it should be +6V for this circuit given the values of *Rf* and *R1*) so we know the circuit is faulty. The voltage on the inverting pin is 0V (it should be +3V) which tells us that the circuit has lost negative feedback and the problem must be either with the op amp or *Rf*. However, we know the problem must be *Rf* and that it has gone open-circuit otherwise there would be +5V on the op amp's inverting pin.

    Note: Once the circuit loses negative feedback, the voltage on the op amp's inverting pin is no-longer exactly the same as on it's non-inverting pin and can be calculated using the output voltage and the voltage divider equation [ie $V_{inverting} = Vout \times \frac{R1}{R1+Rf}$].

20. *R1* has gone high in value. (It's actually gone up to a nudge over 20kΩ but you didn't have to provide that information.)

21. The output voltage has gone down to 4V (it should be +6V for this circuit given the values of *Rf* and *R1*) so we know the circuit is faulty. The voltage on the inverting pin is +3V as it should be and this tells us that the circuit has negative feedback so the op amp must be working. We can see that the circuit still has voltage gain so the problem must be that one of the resistors has changed value. In theory, it could be that *R1* has gone high or that *Rf* has gone low. But the physically small resistors used to implement closed-loo op amp circuits never go low so the problem must be that *R1* has gone high.

22. The op amp is faulty.

23. The output voltage has gone down to 0V (it should be +6V for this circuit given the values of *Rf* and *R1*) so we know the circuit is faulty. The voltage on the inverting pin is 0V (it should be +3V) which tells us that the circuit has lost negative feedback and so the problem must be is either the op amp, *Rf* or *R1*. There is no fault that *Rf* or *R1* can have that would produce 0V on the output of a working op amp in this circuit. So the problem must be the op amp itself.

24. *R1* has gone open-circuit.

25. The output voltage has gone down to 3V (it should be +6V for this circuit given the values of *Rf* and *R1*) so we know the circuit is faulty. The voltage on the inverting pin is +3V as it should be and this tells us that the circuit has negative feedback so the op amp must be working. We can see that the circuit still has a voltage gain of 1 so the problem must be that one of the resistors has changed value. The only change that would cause the voltage gain to go to exactly 1 is *R1* has gone open. This can be tested using the gain equation for this circuit if you replace the value of *R1* with a really large number like 100GΩ.

Section 7

1. Inverting op amp.

2. $Av = -\left(\frac{Rf}{Rin}\right)$

   $Av = -\left(\frac{330k\Omega}{4k7\Omega}\right)$

   $Av = -70.2$

3. Phase inverted (as indicated by the minus sign)

4. ±10V or 20Vp-p (though, in practise, slightly less).

5. $Vin_{(\max)} = \frac{Vout_{(\max)}}{Av}$

   $Vin_{(\max)} = \frac{20Vp-p}{70.2}$

   $Vin_{(\max)} = 285mVpp$

6. 4k7Ω

7. $BW = \frac{GBWP}{Av}$

   $BW = \frac{1MHz}{70.2}$

   $BW = 14.2kHz$

8. $Vin = \frac{Vout}{Av}$

   $Vin = \frac{5V}{70.2}$

   $Vin = 71.2mV$

9. The inverting input is <u>always</u> zero volts for this op amp configuration.

10. Change *Rin* to 33kΩ
    Change *Rf* to 47kΩ

Section 7 (continued)

11. Change *Rf* to 47kΩ.

    It might be tempting to change *Rin* to 33kΩ as this increases the circuit's input resistance. However, in practical inverting op amp circuits *Rin* shouldn't be much greater than about 20kΩ to minimise noise.

12. 100kHz

13. The op amp is faulty.

14. The output voltage has gone up to +*Vcc* (it should be -8V for this circuit given the values of *Rf* and *Rin*) so we know the circuit is faulty. The voltage on the inverting pin is +4V (it should be 0V) which tells us that the circuit has lost negative feedback and the problem must be the op amp. The problem can't be caused by one of the resistors having gone high or open. That's because these problems would either cause the output to be either 0V or some negative voltage.

15. *Rf* has gone high.

16. The output voltage has gone up to -*Vcc* (it should be -8V for this circuit given the values of *Rf* and *Rin*) so we know the circuit is faulty. The voltage on the inverting pin is 0V as it should be and this tells us that the circuit has negative feedback so the op amp must be working. This means then that, as the output voltage is -*Vcc* the op amp must be being overdriven and so the gain has gone up substantially. This would happen if *Rf* has gone high in value. The problem can't be caused by *Rin* having gone low because the physically small resistors used to implement closed-loop op amp circuits never go low in value.

    Note: You may have been tempted to think that *Rf* has gone open but that's not the case here. We know that it can't be, because we know the circuit has negative feedback (see the second sentence in the paragraph above). Had *Rf* gone open, the output voltage would be -12V but the voltage on the inverting pin would be the same as the input voltage (2V in this circuit).

17. *Rin* has gone high. (It's actually gone up to a 80kΩ but you didn't have to provide that information.)

18. The output voltage has gone up to -0.5V (it should be -8V for this circuit given the values of *Rf* and *Rin*) so we know the circuit is faulty. The voltage on the inverting pin is 0V as it should be and this tells us that the circuit has negative feedback so the op amp must be working. This means then that, as the output voltage is smaller than it should be, the voltage gain must have gone down and so there must be a problem with one of the resistors. But, the problem can't be with *Rf* because, it would have to go low in value to cause the gain to go down but the physically small resistors used to implement closed-loop op amp circuits don't go low. So, *Rin* must have gone high in value.

Section 7 (continued)

19. Summing amplifier

20. $Av_{(1)} = -\left(\frac{R4}{R1}\right)$ $Av_{(2)} = -\left(\frac{R4}{R2}\right)$ $Av_{(3)} = -\left(\frac{R4}{R3}\right)$

$Av_{(1)} = -\left(\frac{100k\Omega}{1k\Omega}\right)$ $Av_{(2)} = -\left(\frac{100k\Omega}{25k\Omega}\right)$ $Av_{(3)} = -\left(\frac{100k\Omega}{50k\Omega}\right)$

$Av_{(1)} = -100$ $Av_{(2)} = -4$ $Av_{(3)} = -2$

21. $Vout = Av_{(1)} \times Vin_{(1)}$ $Vout = Av_{(2)} \times Vin_{(2)}$ $Vout = Av_{(3)} \times Vin_{(3)}$

$Vout = -100 \times -0.1V$ $Vout = -4 \times 0.4V$ $Vout = -2 \times 2V$

$Vout = 10V$ $Vout = -1.6V$ $Vout = -4V$

22. $Vout = Vout_{(1)} + Vout_{(2)} + Vout_{(3)}$

$Vout = 10V + -1.6V + -4V$

$Vout = 4.4V$

23. 0V (virtual earth)

24. Rin1 = 1kΩ
Rin2 = 25kΩ
Rin3 = 50kΩ

25. *Vout* would only be affected by the voltages on inputs 2 and 3. For the input voltages given, the output voltage changes to -5.6V.

Proof: $Vout = Vout_{(2)} + Vout_{(3)}$

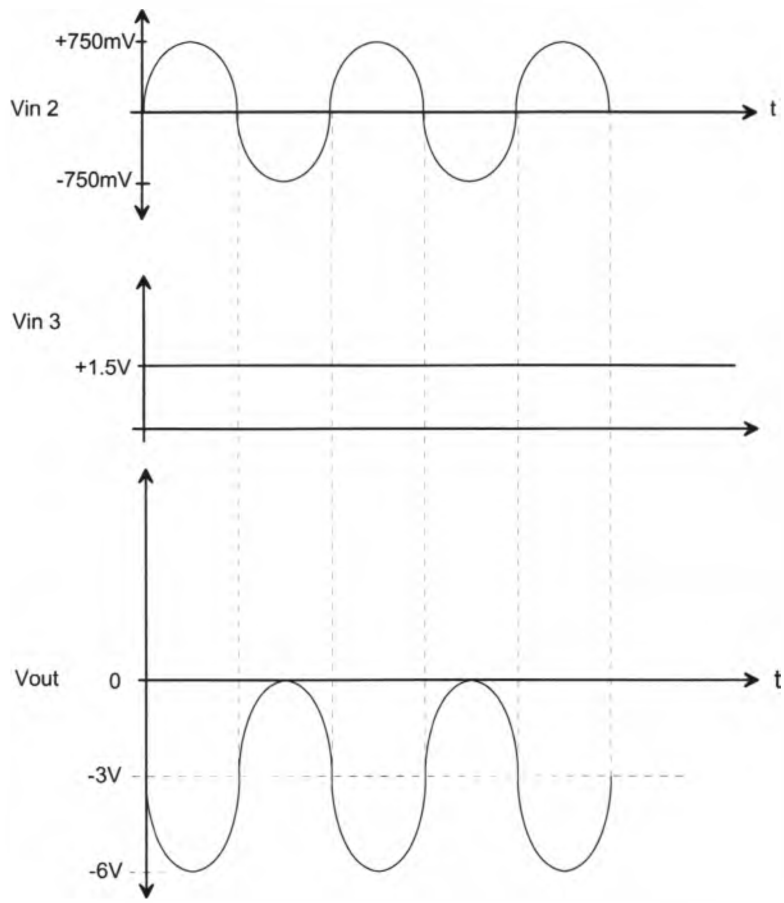
$Vout = -1.6V + -4V$

$Vout = -5.6V$

26. Without *R4* there would be no negative feedback so the gain would be extremely high. Therefore the output voltage would just sit at either +*Vcc* or -*Vcc*.

Section 7 (continued)

27.



Section 8

1. $Av = \frac{R3}{R1}$

   $Av = \frac{150k\Omega}{25k\Omega}$

   $Av = 6$

2. $Vout = (Vin1 - Vin2) \times Av$

   $Vout = (-15mV - 30mV) \times 6$

   $Vout = -270mV$

3. 0V

4. Double both *R3* & *R4* or halve both *R1* & *R2*.